THE CRUSHED STONE JOURNAL

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The National Crushed Stone Association

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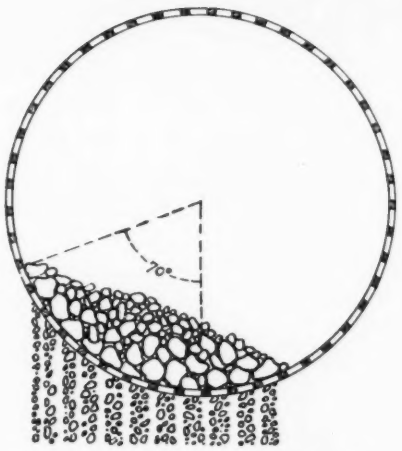

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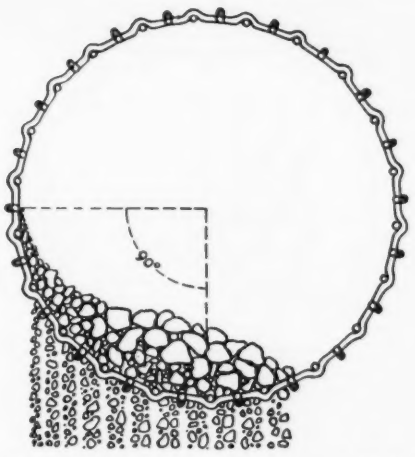

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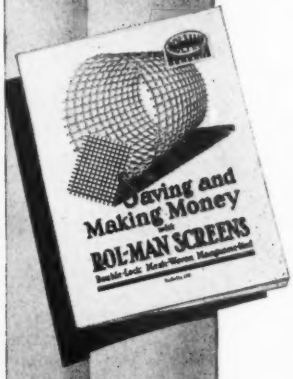

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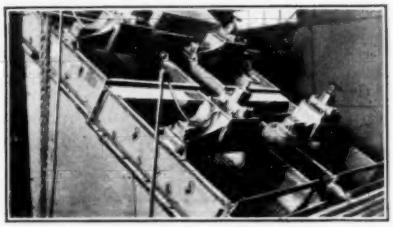

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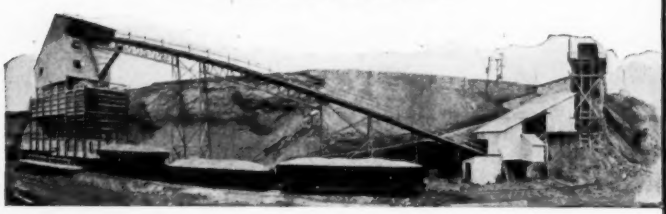

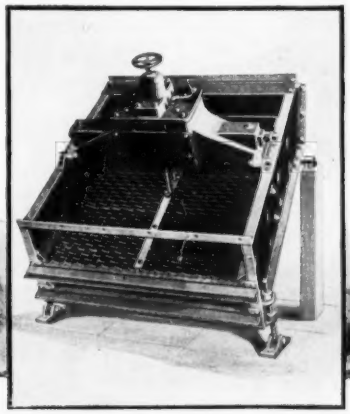

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Further Tests on Crushed Stone and Gravel Concrete

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IN the March, 1929, issue of *The Crushed Stone Journal* a number of test results were published showing the effects of various kinds of coarse aggregates on the compressive strength and modulus of rupture of concrete. The present series of investigations is a continuation of the previously published series.

In the first series the proportions of the concrete were 1:2:3½ by dry, loose volume. In the present series the proportions were so designed that there would be the same cement content per cubic yard in all of the concretes and as nearly as practicable all concretes were mixed to the same consistency.

Method of Proportioning Concrete

In the investigations already reported the method of proportioning by arbitrary volumes resulted in a rather wide variation in cement content per cubic yard of finished concrete and because of this variable, it is difficult to study the effects of the different coarse aggregates on the resulting concrete strengths. Accordingly, in the present tests instead of using identical proportions, such as 1:2:3½, the proportions were varied and the cement content was made 6.3 bags per cubic yard in all cases, as nearly as this was feasible. The procedure for determining the exact proportions to produce the required cement content may be of interest and, accordingly, will be explained in rather complete detail.

HIGH POINTS OF THE PAPER

1. It has been the practice to specify the proportions of concrete in terms of arbitrary volumes of the cement, fine and coarse aggregates such as 1:2:3½. This practice instead of producing concrete of like quality for all aggregates actually results in concretes which are dissimilar in many respects such as characterized by:
   (a) Wide differences in strengths.
   (b) Wide differences in cement, fine and coarse aggregate content per cubic yard.
   (c) Wide differences in workability.
   (d) Wide differences in the amount of mixing water required.

2. The ideal proportions for road concrete are those which will produce workable concrete having the required beam strength expressed in terms of "modulus of rupture," rather than a given compressive strength.

3. All concretes in the present series were proportioned to have a cement content of 6.3 bags per cubic yard. There results a higher sand content and a higher water content, the higher the percentage of voids in the coarse aggregate. Notwithstanding this fact the angular coarse aggregate concrete shows a superior average modulus of rupture. However, it is not fair to assume that the angular aggregate will always be superior to the rounded aggregate for producing concrete of high beam strength. Some gravels, particularly the calcareous gravels, containing crushed fragments are superior to some crushed stones.

4. It is evident that weak gravels as shown by high abrasive loss in the Gravel Abrasion Tests produce concrete having low beam strength. It is also evident that smooth rounded gravels cause a lowered beam strength.

5. There is no definite relation between crushing strength and modulus of rupture of concrete when different coarse aggregates are used. Weak aggregates may produce concrete of high compressive strength but very low beam strength.

Method of Proportioning Concrete for Equal Cement Content

It must be apparent that a given volume of concrete must be composed of the sum of the solid volumes of cement, and fine and coarse aggregates plus the volume of water and air in the mixture. Obviously, if we are considering two coarse aggregates, one having a high void content and the other a low void content, or conversely, one having a low solid volume and the other a high solid volume, the lack of solid volume in the one coarse aggregate must be supplied through additional solid volume of sand or water, or both, if the two concretes made with different coarse aggregates are to have the same resulting cement content per cubic yard.

The quantity of coarse aggregate which can be mixed in concrete is controlled by the degree of workability desired in the mix. In general, a high percentage of coarse aggregate will produce a harsh working mix

and as the ratio of fine to coarse aggregate is increased, that is, as more sand is added and stone is subtracted, the mix will become more workable. For the sake of economy and likewise for the sake of imparting to the concrete other highly desirable features, such as low shrinkage and low absorption, it is generally desirable that as much coarse aggregate be used in the mix as the necessary degree of workability will permit. The method of procedure described by Profs. Talbot and Richart in bulletin No. 137 of the Engineering Experiment Station of the University of Illinois, entitled, "The Strength of Concrete, Its Relation to the Cement, Aggregates and Water" was followed to the extent of selecting the amount of coarse aggregate to be used in the mix. The determination of the solid volume of the coarse aggregate was made by the use of the formula:

$$\frac{b}{b_o} = 0.775$$

where b = solid volume of the coarse aggregate in a cubic foot of concrete,

b_o = solid volume of coarse aggregate in a cubic foot of coarse aggregate, measured dry and loose.

The quantity, 0.775, is a value determined by experiment and is quite applicable to mixes suitable for concrete highway construction and having a cement content of 6.3 bags per cubic yard. It is possible that this value may be increased or decreased slightly depending upon the gradation and characteristics of the coarse aggregates.

Having determined the solid volume of the coarse aggregate required in the mix in the above manner and also having decided what cement content is desired, there remains the determination of the amount of water and sand necessary to give concrete of the desired consistency. This determination requires that small trial batches of concrete be made, first, assuming a given water-ratio and calculating, on the basis of solid volumes the amount of sand required to produce concrete of the necessary cement content. The trial batch may show that the right consistency is not obtained with the assumed quantity of water in which case either more or less water must be used in the next trial batch and the process of calculation and the trial mixing must be repeated.

Actually the laboratory procedure and calculations are extremely simple and if the first trial batch is purposely made up too dry, it may be used as a second trial batch merely by adding additional water to it. This procedure is not strictly accurate but serves admirably in approaching closely to the final mix desired. Complete calculations in connection with the details of procedure in arriving at the required mix are given as follows:

Example of Procedure in Obtaining Concrete Proportions

Basis of Proportions:

Cement content to equal 6.3 bags per cubic yard.

Consistency, flow to equal 165, slump 1-2 inches.

Solid volume of coarse aggregate in mix to be obtained from formula—

$$\frac{b}{b_o} = 0.775$$

b = solid volume of coarse aggregate in cubic foot of concrete.

b_o = solid volume of coarse aggregate in cubic foot of coarse aggregate.

0.775 is a constant found by experiment to be suitable.

Procedure:

1. Obtain apparent specific gravity of cement, sand and coarse aggregate by standard methods.
2. Obtain weight per cubic foot, dry and loose of sand and coarse aggregate.
3. Assume cubic foot of cement to weigh 94 lbs.
4. Calculate solid volume of cement, sand and coarse aggregates.

$$\text{Solid volume} = \frac{\text{weight per cu. ft.}}{\text{Sp. Gr. x } 62.4}$$

5. Estimate required water-ratio and obtain sum of solid volumes of cement, coarse aggregate and water in a cubic yard of concrete and obtain solid volume of sand required by subtracting the above sum from 27 cu. ft.
6. Make up small trial batch proportioned as in No. 5 above to determine if of correct consistency.
7. If too dry, add more water until right consistency is obtained. This will permit of a close estimate of the right amount of water to use.
8. Make up new trial batch based on revised quantities.
9. Measure volume of concrete batch which should equal sum of solid volumes of materials used except for volume of included air which approximates 1 per cent of the volume of road concrete.

Example

Cement: Sp. Gr. = 3.12, wt. per cu. ft. = 94 lbs., solid wt. = 3.12 x 62.4 = 195 lbs.
Sand: Sp. Gr. = 2.68, wt. per cu. ft. = 98.7 lbs., solid wt. = 2.68 x 62.4 = 167 lbs.
Stone: Sp. Gr. = 2.76, wt. per cu. ft. = 95.7 lbs., solid wt. = 2.76 x 62.4 = 172 lbs.

Solid volume of stone in cu. ft. of stone $= \frac{95.7}{2.76 \times 62.4}$

$= 0.556$ cu. ft. $= b_o$ $\frac{b}{b_o} = 0.775$, $b = b_o \times 0.775 =$

$0.556 \times 0.775 = 0.431$ cu. ft. of solid stone in each cubic foot of concrete.

Assume W/C = 0.75

Cubic Foot of Solid Materials in Cubic Yard of Concrete

Cement	$\frac{6.3 \times 94}{3.12 \times 62.4}$	= 3.04 cu. ft.
Stone	0.431 x 27	= 11.63
Water	0.75 x 6.3	= 4.72
Air	0.01 x 27	= 0.27
		19.66 cu. ft. of materials

exclusive of sand.

27 — 19.66 = 7.44 cu. ft. of solid sand required.

For trial batch use ½ cu. ft. of concrete = 1/54 cu. yd. giving the following quantities of materials:

Cement	3.04 x 1/54 x 195	= 10.97 lbs.
Sand	7.44 x 1/54 x 167	= 23.0 "
Stone	11.63 x 1/54 x 172	= 37.10 "
Water	4.72 x1/54 x 62.4	= 5.45 "
Flow		130

The above quantities when mixed had a flow of 130 instead of the desired 165, hence, more water (0.22 lbs.) was immediately added to this same batch giving a W/C = 0.78 and a flow of 165.

It was estimated that 0.77 W/C would give the right consistency when used with a fresh batch, and a fresh trial batch calculated on this basis as follows proved to have the desired consistency.

Cement	3.04 cu. ft.
Stone	11.63
Water (0.77 x 6.3)	4.85
Air	0.27
	19.79 cu. ft. of materials exclusive of sand.

27 — 19.79 = 7.21 cu. ft. of solid sand required in a cubic yard of concrete.

Proportions for New Trial Batch of ½ cu. ft. or 1-54 cu. yd. of Concrete

Cement		10.97 lbs.
Sand	7.21 x 1/54 x 167	= 22.3
Stone		37.10
Water	4.85 x 1/54 x 62.4	= 5.60

The proportions by dry, loose volume are then:

$\frac{10.97}{94} : \frac{22.3}{98.7} : \frac{37.1}{95.7} = 0.116 : 0.226 : 0.388 = 1 : 1.95 : 3.34$

A trial batch as small as 1/4 cubic foot in volume will be suitable for determining with reasonable accuracy the required proportions but a larger batch is more accurate.

In the preceding manner the proportions for the various coarse aggregates used in the present investigations were determined.

Characteristics of Coarse Aggregates Used

For the sake of completeness the characteristics of the coarse aggregates used in the first series of investigations and also in the present series are repeated.

In Table I are shown the various physical characteristics of the coarse aggregates used. The column headed "% Wear" contains the results of the Deval Abrasion Test on stone samples and the Gravel Abrasion Test, as described in Bulletin 1216 of the U. S. Department of Agriculture, on gravel samples. It is to be noted that the stone extends in percentage of wear from 2.0 to 7.0 and the gravel from 3.5 to 28.1. It is believed that these respective ranges in percentage of wear include most of the commercial

Table I. Showing Characteristics of Coarse Aggregates

No.	Materials	% Retained—Square Openings					% Wear	Apparent Sp. Gr.	Wt./cu.ft. (loose)	% Voids (loose)	% Absorption
		2"	1½"	1"	½"	#4					
2	Stone	....	9	58	83	98	3.5	2.69	91.7	45.3	0.3
3	Gravel	....	2	19	78	99	10.5	2.30	87.3	39.0	2.9
5	Stone	....	3	45	91	99	2.9	2.96	92.3	50.0	0.2
6	Gravel	....	13	41	82	98	16.9	2.63	102.7	37.5	0.7
7	Stone	....	10	39	74	97	7.0	2.58	89.5	44.3	1.3
8	Gravel	....	8	35	78	98	10.7	2.69	103.7	38.2	1.1
9	Stone	8	31	61	85	95	6.7	2.67	95.7	42.5	0.3
12	Gravel	....	....	11	74	99	5.0	2.56	94.6	40.8	0.7
13	Stone	....	13	44	85	98	3.5	2.44	86.2	43.3	2.0
17	Gravel	2	13	51	92	100	8.6	2.55	98.9	37.8	0.6
23	Stone	....	6	33	75	94	2.0	2.62	93.6	42.7	0.1
24	Gravel	1	21	58	91	100	3.5	2.72	103.6	38.8	0.8
27	Stone	....	13	39	71	95	2.8	2.77	97.2	43.8	0.2
28	Gravel	....	3	13	51	93	26.2	2.56	104.9	34.3	0.8
29	Gravel	....	3	36	83	99	3.5	2.56	99.3	37.7	1.0
32	Stone	....	7	50	76	95	2.9	2.61	95.0	41.3	0.3
31	Gravel	....	15	40	71	97	28.1	2.61	103.9	36.2	0.7
35-1	Stone	....	28	57	85	100	3.3	2.76	95.7	44.5	0.3
35-2	Stone	....	28	57	85	100	3.3	2.76	95.7	44.5	0.3

coarse aggregates now being supplied to the market. There is no question that samples Nos. 28 and 31 are far softer than the gravel most commonly used but, none the less, both of these materials are used commercially. In all cases the tests were made in accordance with the standard methods of the American Society for Testing Materials when such standard methods exist. The weight per cubic foot, "loose" was determined in the Standard A. S. T. M. cubic foot measure by merely shoveling the coarse aggregate into the measure and striking off the top. The apparent specific gravity was obtained by the "overflow" apparatus as described in Bulletin 1216 and the percentage of absorption was determined on the same sample as used in determining the apparent specific gravity. When the gravel was heterogeneous in character, an effort was made to select a specific gravity sample which was representative of the material. The percentage of voids was calculated from the weight per cubic foot and the apparent specific gravity by the formula—

$$\text{Percentage of voids} = 100 \left\{ 1 - \frac{\text{Wt. per Cu. Ft.}}{\text{Ap. Sp. Gr. x } 62.4} \right\}$$

Description of Gravel

The gravel samples had the following characteristics:

Sample No. 3—per cent wear, 10.5. This is a chert gravel composed largely of hard, smooth chert fragments with a few softer fragments of sandstone or shale; sub-angular in shape and somewhat badly weathered.

Sample No. 6—per cent wear, 16.9. This is a heterogeneous mixture of quartz, gneiss, conglomerate, sandstone and igneous rocks. The surfaces are not particularly smooth and many of the fragments appear to be badly weathered and weak, quite angular and a considerable amount of crushed fragments.

Sample No. 8—per cent wear, 10.7. This is essentially a limestone gravel with a small percentage of sandstone and igneous fragments. The surfaces are rounded and somewhat rough; contains a considerable percentage of crushed and angular fragments.

Sample No. 12—per cent wear, 5.0. This is largely a chert gravel with smooth, although slightly pitted surfaces. The fragments are sub-angular in shape.

Sample No. 17—per cent wear, 8.6. This sample shows the same characteristics as sample No. 12.

Sample No. 24—per cent wear, 3.5. This sample is composed of fragments of limestone or dolomite, sandstone and rocks of igneous origin with a small percentage of chert and quartz. There is a considerable quantity of crushed fragments with rough surfaces.

Sample No. 28—per cent wear, 26.2. This is a badly weathered quartz gravel, surfaces rough and pitted, fragments weak, sub-angular in shape.

Sample No. 29—per cent wear, 3.5. This is a heterogeneous gravel composed of fragments of sandstone, shale, quartz, and metamorphosed fragments of igneous origin. Surfaces vary from smooth to very rough; contains crushed fragments. Shape varies from rounded to quite angular.

Fine Aggregate

The fine aggregate used in all cases was Potomac River sand having the following gradation:

Retained on	*Per cent*
4	3.6
10	23.2
14	29.4
28	47.0
48	82.0
100	96.8
Passing 100	3.2

Fineness modulus = 2.82

Weight per cubic foot, dry, loose = 98.7 pounds.

There is one change to be noted in Table I, namely, the per cent of wear for stone No. 13. It has been found that this particular stone is variable in its physical characteristics and parts of the quarry contain hard material, other parts soft material. Evidently the sample which was first tested for abrasion loss was of the harder variety and does not truly represent the coarse aggregate used in the concrete tests. It was thought well, therefore, to repeat the abrasion test, using as a sample an average of the material selected from the crushed aggregate. It is realized, of course, that hand-broken, rather than crushed pieces, are specified for use in the Deval Abrasion Test but the difference in results obtained is usually quite small and the per cent of loss obtained in this manner, 5.9, is considered to be much more representative of the material actually used than the value of 3.5 formerly reported.

The method of mixing the concrete, of moulding and storing the specimens and the methods of testing were all identical with those described in the March, 1929, issue of *The Crushed Stone Journal* and will not be repeated at the present time.

Discussion of Results

In the results of the tests as shown in Table II it is to be noted that the cement contents per cubic yard of concrete deviate very little from the designed quantity, 6.3 bags. The slight deviations are due to unavoidable experimental errors. The consistencies were as nearly alike as it was practicable to make them, according to measurements by the standard slump test and flow table and the aim was to produce concrete having a flow of 165 with a slump varying between 1 and 2 inches. As would be expected there is a variable relation of sand to coarse aggregate because of the variable characteristics of the coarse aggregates. In general, the stone required a larger quantity of sand than the gravel, and also because of this fact, a higher water-ratio was necessary.

Table II.—Showing Properties of Concrete with Different Coarse Aggregate Graded as Received. Approximately Same Cement Content and Same Consistency. Age 28 Days. Cured in Moist Room.

No.	Coarse Aggregate	Proportions Dry Cement	Proportions Dry Sand	Proportions Volume Coarse Aggregate	Cement Bags per cu. yd.	Corrected W/C	Slump	Flow	Compressive Strength lbs. per sq. in.	Modulus of Rupture lbs. per sq. in.
35	Stone....	1	1.99	3.33	6.27	0.77	1.5	172	4490	768
2	Stone....	1	1.99	3.33	6.30	0.78	1.75	176	4300	745
3	Gravel...	1	1.67	3.43	6.33	0.69	1.5	159	4750	633
5	Stone....	1	2.19	3.29	6.28	0.83	1.25	169	4030	715
6	Gravel...	1	1.66	3.32	6.30	0.71	2.25	170	4310	607
7	Stone....	1	1.92	3.32	6.32	0.77	1.5	164	4890	755
8	Gravel...	1	1.69	3.31	6.30	0.70	2.0	168	5020	786
9	Stone....	1	1.83	3.30	6.28	0.79	1.25	159	4170	647
12	Gravel...	1	1.79	3.31	6.30	0.77	1.5	163	4360	650
13	Stone....	1	1.92	3.36	6.34	0.78	2.0	164	4890	760
17	Gravel...	1	1.73	3.32	6.30	0.68	2.0	164	4610	642
23	Stone....	1	1.87	3.32	6.31	0.78	1.75	162	4790	759
24	Gravel...	1	1.79	3.34	6.28	0.69	2.0	165	4850	707
27	Stone....	1	1.92	3.28	6.30	0.80	1.5	166	4480	769
28	Gravel...	1	1.51	3.36	6.32	0.71	1.5	160	4720	626
29	Gravel...	1	1.71	3.33	6.31	0.70	2.0	166	4730	704
32	Stone....	1	1.79	3.41	6.27	0.77	1.75	163	4660	690
31	Gravel...	1	1.57	3.41	6.27	0.70	1.5	163	4240	531
28-1	Gravel...	1	1.60	3.24	6.32	0.73	1.75	164	4480	613
31-1	Gravel...	1	1.64	3.29	6.29	0.72	1.75	160	4060	587
35	Stone....	1	1.98	3.29	6.30	0.76	1.75	164	4580	770

The strength results in compression and in bending are shown in the last two columns of the table. It will be noted that there are two mixes numbered 35. The reason for this is that stone No. 35 is used in the laboratory as a standard coarse aggregate and the concrete containing this stone is mixed for comparison with other concrete mixtures. The number of molds available did not permit of making mixtures of all of the aggregates on the same day. But by using a standard coarse aggregate for comparison purposes, it becomes possible to determine if unsuspected influences are affecting the true comparison of the various aggregates under test. Apparently, in these particular tests the standard coarse aggregate concrete did not have greatly different strengths though mixed on different days. Accordingly, the strength results obtained with the various coarse aggregates may be compared with confidence.

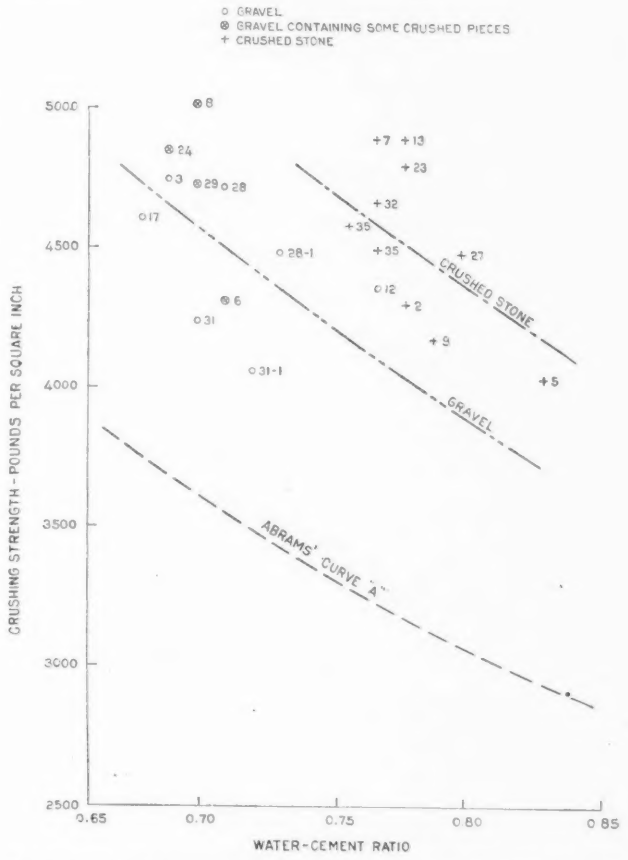

FIGURE 1.—*Water-cement Ratio vs. Crushing Strength when various Aggregates are used. 6.3 bags of cement per cubic yard. Age 28 days.*

The significance of the test results tabulated in Table II can best be comprehended by referring to Figs. 1, 2 and 3. Fig. 1 shows the relation between crushing strength and water-cement ratio. For the sake of comparison, Abrams' curve "A" has been plotted on this diagram and it will be noted that all of the test results lie considerably above this curve, indicating perhaps, that the strength of the particular brand of cement used in these tests exceeded that upon which Abrams'

curve was based a number of years ago. Although the test results do not lend themselves to the drawing of an average water-cement ratio curve, it seems to be outstanding that the line averaging the crushing strengths of the stone concrete lies somewhat to the right of that applying to the particular gravel concretes tested. Whether these two curves may be considered typical of the gravels and stones to be expected in service is not known, but, nevertheless, the coarse aggregates used represent a considerable range in charactristics. If these results are typical, then, it might be said that in a broad, general way, the water-cement ratio which may be used with crushed stone concrete is higher than that necessary with gravel concrete of like consistency.

For the particular test results shown the crushed stone concrete has 0.07 (about ½ gallon of water per bag of cement) higher water-ratio than the gravel concrete for equal crushing strengths. However, as will be seen by the scattered results, it is not safe to make any general statement as to the difference in water-ratio allowable as between crushed stone and gravel for equal strengths. It is quite apparent that the water-ratio necessary to produce a given strength is

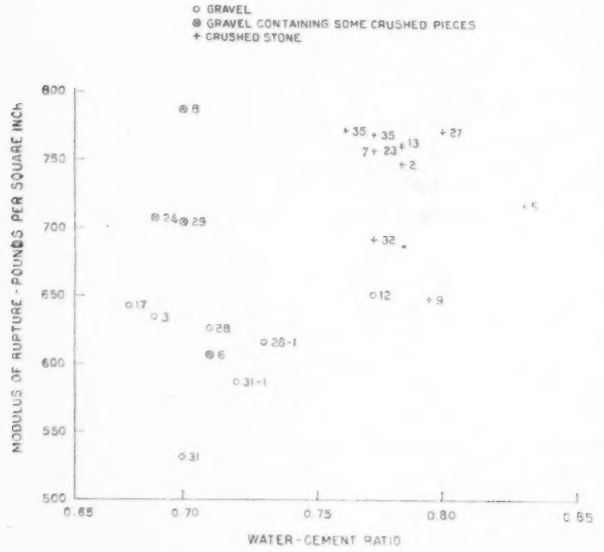

FIGURE 2.—*Modulus of Rupture vs. Water-cement Ratio when various Aggregates are used. 6.3 bags of cement per cubic yard. Age 28 days*

dependent upon the gradation and other characteristics of the aggregates and, naturally, is also dependent upon the strength of the cement. It is to be remembered that the range of water-ratio shown in Fig. 1 is

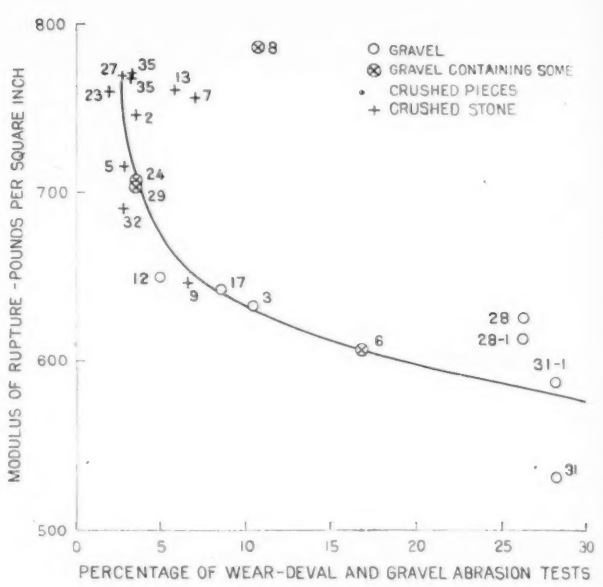

FIGURE 3.—*Effect of Percentage of Wear on Modulus of Rupture. 6.3 bags of Cement per cubic yard. Age 28 days*

very small in comparison with the wide range necessary to plot a complete water-ratio crushing strength curve such as shown originally by Abrams, and the deviation of these individual results for the different aggregates from an average curve drawn through the points shown, is probably no greater than the deviation of the individual results used in obtaining Abrams' curve. If an average water-ratio were assumed, the deviation in strength to be expected, depending upon the characteristics of the aggregates used, does not exceed about 500 pounds per square inch.

In Fig. 2 is shown the relation between modulus of rupture of concrete and the water-cement ratio. For the same water-cement ratio there is seen to be a rather wide range in strength results. For instance, for a water-ratio of approximately 0.70 the range in modulus of rupture varies from a maximum of 786 to a minimum of 531. The maximum value is approximately 150 per cent of the minimum. The minimum value is obtained with a coarse aggregate which is decidedly weak in structure and the maximum value with a good grade of limestone gravel containing crushed fragments. It is to be noted on this diagram that the crushed stone concretes average considerably higher in modulus of rupture than the gravel concretes, notwithstanding the fact that more water was necessary in the crushed stone mixes than in the gravel mixes. In all cases the cement content was 6.3

bags per cubic yard. The extra water was necessary because of the additional sand used in the crushed stone mixes.

In designing concrete mixes for cross-breaking resistance, it is indicated by the test results that a higher water ratio may be used with crushed stone concrete than with the gravel concrete when both concretes have equal cement content per cubic yard and if these results are typical, a higher cross-breaking strength may still be expected with the stone concrete than with the gravel concrete. There are exceptions to this as will be noted by the fact that some of the gravels, particularly those having crushed pieces, run higher in cross-breaking strengths than some of the stones. Reference to Table II will show several cases where, although the gravel concrete slightly exceeds the stone in compression, their strength values are reversed in cross-breaking. This serves to emphasize the fact that it is not safe to assume that because the concrete has high compressive resistance it will likewise have high resistance in cross-bending.

In Fig. 3 results are shown for the modulus of rupture of concrete and percentage of wear of both the stone and the gravel as determined by the Deval Abrasion Test and by the Gravel Abrasion Test in the case of the stone and gravel samples respectively. It is quite evident that there is a rather decided trend in the results shown. Those materials which have a particularly high abrasion loss also have a low modulus of rupture and those having a low abrasion loss have a high modulus of rupture. There is an exception to this in the single instance of sample No. 8, a limestone gravel containing crushed fragments. This curve does not seem unreasonable for those aggregates having a high abrasion loss are composed of fragments which fracture rather easily and when subjected to tension they readily pull apart. Some doubt has existed in the minds of testing engineers as to the value of the abrasion test, whether it be the old Deval Abrasion Test or the newer Gravel Abrasion Test as used for gravel samples. Certainly, the present test results show very strongly that the abrasion test may be of considerable value in indicating the effect which the coarse aggregate will have on the modulus of rupture of concrete. It seems to be the case that weak fragments will produce low cross-bending resistance. There does not seem to be any particular effect on cross-bending resistance, however, when the percentage of wear is under approximately 10 per cent, for both high and low results are obtained in modulus of rupture with materials varying from approximately three to approximately ten per cent.

Conclusions

The following conclusions seem to be warranted on the basis of the particular materials used in these tests:

1. When crushed stone and gravel concretes have like cement contents per cubic yard, a somewhat higher water-ratio, equalling approximately 0.07, (½ gal. per bag of cement) may be used with crushed stone concrete than with gravel concrete. This is merely an average value from which there may be considerable variation depending upon individual aggregate characteristics.

2. Notwithstanding the higher water-ratios necessary in the crushed stone concretes than in the gravel concretes, the crushed stone concretes in these tests average considerably higher in modulus of rupture than the gravel concretes. There are individual exceptions and reversals of this rule particularly when the gravel contains crushed fragments.

3. The relative cross-breaking resistance of concretes cannot be judged by their relative compressive strengths. Aggregates of extremely poor quality may give comparatively high compressive resistance but have low resistance to bending. The quality of the aggregates affects both compressive and bending resistance of concrete but is more important in influencing the cross-bending than the compressive resistance.

4. The Gravel Abrasion Test seems to be a good measure of the characteristics of gravels which may produce concrete of low cross-bending resistance. A very high percentage of wear is indicative of weak material which will weaken the beam strength of concrete.

5. The rounded smooth surfaces of certain gravels seems to adversely affect the beam strength of concrete. (Samples 3, 12 and 17).

It may seem that the difference in modulus of rupture obtained with these various coarse aggregates is comparatively small and unimportant. Actually small differences in modulus of rupture may be highly important. It must be remembered that the modulus of rupture is a measure of the resistance of concrete to cracking. The modulus of rupture test is of the greatest importance for designing concrete for concrete highways, because it is almost invariably the case that the tensile stresses produced by bending in concrete highways under the action of traffic are high, and for the sake of economy, and because no danger of loss of life is involved, a concrete road slab is designed with very little factor of safety against cracking under

(*Continued on page* 28)

Effect of Type and Gradation of Coarse Aggregate Upon the Strength of Concrete[1]

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THE compression test has been employed almost universally in the past for measuring the quality of Portland cement concrete. Applied to structural concrete for general purposes, this measure of quality has proved quite adequate, because in such cases the crushing strength is the property of greatest interest. When the concrete is to be used in the construction of pavements, however, the crushing strength, although still important, is no longer the critical factor. Concrete pavements should be designed to support, without cracking, heavy concentrated loads which subject them to high bending stresses.

Flexural strength thus becomes the most important strength characteristic, and the factors which affect it become of interest to the highway engineer, even though they may not be of primary importance in other types of concrete construction. To illustrate this distinction: It has been demonstrated through research that within quite wide limits the kind of coarse aggregate employed has relatively little effect on the crushing strength of concrete, provided the mixture is workable and the aggregates sound. This is not true in the case of flexure, however, all of the test data so far accumulated indicating that such factors as surface texture, angularity of fragments, and other characteristics of the aggregates affect the flexural and tensile strength of the concrete to a marked degree. The tests which are reported in this paper substantiate earlier experiments along the same lines and indicate that the character of aggregate must be given consideration in the design of concrete for pavements.

These tests also indicate that the compressive strength of concrete may be affected by the character of the coarse aggregate to a considerably greater extent than has been shown by prior investigations.

A Variety of Coarse Aggregates and Aggregate Gradings Tested

The tests were conducted primarily for the purpose of determining the effect of type of coarse aggregate upon the flexural strength of concrete. Auxiliary data regarding resistance to direct tension as well as crushing strength and yield of concrete were also obtained.

[1] From June, 1929, *Public Roads*.

Seventeen typical coarse aggregates, including seven gravels, seven crushed stones and three blast-furnace slags were selected from various sources so as to give as wide a range in physical characteristics as possible. These were tested in concrete, using four typical coarse aggregate gradings as well as four paving mixes. The sand used was a typical high-grade concrete sand. Its physical properties as well as those of the Portland cement employed in the tests are given in Table 1. The physical properties of the various coarse aggregates are given in Tables 2 and 3.

Grading No.	Percentage passing—square openings				
	⅛-inch	¼-inch	¾-inch	1¼-inch	2-inch
1	0	0	15	40	100
2	0	0	30	55	100
3	0	5	45	70	100
4	0	5	55	100	100

TABLE 1.—*Physical properties of cement and fine aggregate used in all tests*

CEMENT

Fineness, percentage retained on 200-mesh sieve, 11.5.
Time of set (Gillmore):
Initial, 3 hours 10 minutes.
Final, 5 hours 35 minutes.
Steam test for soundness, O. K.
Normal consistency, 23.1 per cent.
Tensile strength (pounds per square inch, 1:3 Ottawa sand morta):

	Pounds
7 days	285
28	380

FINE AGGREGATE

Sieve analysis:

Total retained on ¼-inch screen, per cent	1
Total retained on No. 10 sieve, per cent	12
Total retained on No. 20 sieve, per cent	25
Total retained on No. 30 sieve, per cent	42
Total retained on No. 40 sieve, per cent	72
Total retained on No. 50 sieve, per cent	93
Total retained on No. 100 sieve, per cent	100
Silt and clay, per cent	0.3
Apparent specific gravity	2.66

Each coarse aggregate was separated into four sizes at the laboratory and recombined into four definite gradings as shown below. These gradings will be referred to by number and it should be noted that they range from coarse to fine in numerical order of designation.

Weight in pounds per cubic foot (dry rodded) 104
Organic matter (color test) .....Satisfactory.
Strength ratio:
7 days 117
28 days 120
Description: Sand consists essentially of subangular grains of quartz, sandstone and shale, slate and feldspar.

Table 4 gives the weight per cubic foot (dry rodded) and the percentage of voids for each coarse aggregate and for each grading.

All aggregates are identified by number rather than by source of supply.

In outlining this series of tests it was thought advisable to include more than one proportion, and for this reason four nominal mixes (based on dry-rodded volumes) were included, with the following proportions:

Mix No. 1—1:1.6:3.
Mix No. 2—1:1.6:4.
Mix No. 3—1:2:4.
Mix No. 4—1:2:4½.

Mixes No. 1 and No. 2 were designed to correspond approximately to 1:2:3 and 1:2:4 field mixes, respectively.

It will be noted that mix No. 4 (1:2:4½) is the only one which does not conform to present practice. This proportion was used in an endeavor to determine the manner in which the lower sanded mixes behave in flexure as compared to mixes containing smaller amounts of coarse aggregate, but with the same sand-cement ratio.

Fabrication and Testing of Specimens Described

The procedure followed was to make up specimens for Mix No. 1 and grading No. 1, using all aggregates, on the same day. Gradings No. 2, No. 3, and No. 4 were then made in turn on following days. This was repeated for mixes No. 2, No. 3, and No. 4, in the order named, so that the first round of tests consisted of the four mixes and the four gradings for each of the gravel and stone aggregates and two mixes and four gradings of each for the slag aggregates, the harsher mixes, No. 2 and No. 4, not being used with the slags. This required 16 working days to complete one round of tests and, where the quantity of material permitted, four complete rounds were made, making a total of 64 batches of concrete for each aggregate. Thus the general averages given in Table 5 are in practically all cases based on tests on 64 specimens. Each batch of concrete was large enough to make one 6 by 6 by 30 inch beam and one 6 by 21 inch tension cylinder with some excess. The volume of concrete in each batch was measured for yield determination.

TABLE 2.—*Physical properties of coarse aggregates*

Aggregate No.	Per cent wear	Per cent absorption	Specific gravity	Per cent crushed material
40 (trap)	[1] 2.4	0.09	2.91	100
44 (siliceous gravel)	[2] 9.9	.58	2.59	[3] 13 to 28
46 (siliceous limestone)	[1] 3.0	.04	2.76	100
50 (siliceous gravel)	[2] 10.8	.98	2.60	45
60 (granite)	[1] 2.0	.17	2.61	100
61 (sandstone)	[1] 13.2	4.55	2.23	100
62 (cherty limestone)	[1] 3.5	.16	2.66	100
63 [4] (argillaceous limestone)	[1] 6.8	4.42	2.30	100
63a [5] (argillaceous limestone)	[1] 10.4	6.56	2.18	100
64 (siliceous gravel)	[2] 14.5	.50	2.65	20
65 (siliceous gravel)	[2] 13.4	.36	2.61	[3] 46 to 76
66 (limestone gravel)	[2] 9.8	1.23	2.64	[3] 33 to 39
67 (limestone gravel)	[1] 15.1	2.17	2.57	[3] 67 to 92
68 (siliceous gravel)	[2] 12.8	.32	2.58	15
69 (slag)	[1] 22.5	.....	1.83	100
70 (slag)	[1] 13.7	.....	2.06	100
71 (slag)	[1] 12.2	.....	2.27	100
72 (shell limestone)	[1] 7.0	1.87	2.47	100

[1] Test made on crushed material.
[2] Standard test for gravel.
[3] The percentage of crushed material in different gradings was as follows:

Aggregate No.	Grading No. 1	2	3	4
44	13	14	28	20
65	50	46	76	67
66	33	33	35	39
67	71	67	92	88

[4] First shipment of material.
[5] Second shipment of material.

TABLE 3.—*Mineral composition of coarse aggregates*

Aggregate No.	Mineral composition
40	Trap—Diabase and basalt.
44	Gravel—Quartzite, 65 per cent; quartz, 30 per cent; ironstone concretions, 2 per cent; chert, 3 per cent.
46	Siliceous limestone—Massive limestone, 98 per cent; lime, calcite veins, or pure calcite pieces, 2 per cent.
50	Gravel—Quartzite, 60 per cent; gneiss, 20 per cent; slate, 15 per cent; chert, 1 per cent; basic igneous, 4 per cent.
60	Granite—Dark, 25 per cent; gray, 10 per cent; pink, 65 per cent.
61	Sandstone—Rounded fragments.
62	Cherty limestone—Pure limestone, 30 per cent; chert limestone, 70 per cent.
63	Argillaceous limestone—Light, 50 per cent; dark, 50 per cent.
64	Gravel—Milk quartz, 10 per cent; gneiss, 80 per cent; badly weathered gneiss, 10 per cent.
65	Gravel—Quartz, 90 per cent; gneiss, schist, and basic minerals, 10 per cent.
66	Gravel—Cherty dolomite (3 colors).
67	Gravel limestone—Thin rounded limestone, 75 per cent; chert, 5 per cent; basic rocks, granites, 20 per cent.
68	Gravel—Granular milk quartz, 80 per cent; rotten chert, 15 per cent; gneiss, 5 per cent.
69	Slag.
70	Do.
71	Do.
72	Limestone—Shell limestone.

All mixing was done by hand in dry pans, the amount of water used being that required to produce a consistency corresponding to a flow of 150.[1] Steel forms resting on steel plates were used for the beams, while the cylinders also rested on steel plates. The concrete was placed in the beam molds in two layers, each layer being rodded about thirty-five times with a ⅝-inch

[1] Percentage of original diameter of the mass after 15 drops of ½-inch in ten seconds on a 30-inch flow table.

TABLE 4.—*Weight per cubic foot and percentage of voids of coarse aggregates*

Aggregate No.	Grading No. 1		Grading No. 2		Grading No. 3		Grading No. 4	
	Weight per cubic foot	Voids	Weight per cubic foot	Voids	Weight per cubic foot	Voids	Weight per cubic foot	Voids
	Pounds	*P. ct.*	*Pounds*	*P. ct.*	*Pounds*	*P. ct.*	*Pounds*	*P. ct.*
40 (trap)	105	42	105	42	106	42	105	42
44 (siliceous gravel)	110	32	111	31	113	30	110	32
46 (siliceous limestone)	101	41	101	41	102	41	102	41
50 (siliceous gravel)	105	35	106	35	108	33	108	33
60 (granite)	99	39	100	39	101	38	100	39
61 (sandstone)	88	37	88	37	90	35	90	35
62 (cherty limestone)	99	40	100	40	100	40	100	40
63 [1] (argillaceous limestone)	88	39	88	39	90	38	90	38
63a [2] (argillaceous limestone)	85	38	86	37	87	36		
64 (siliceous gravel)	109	34	111	33	111	33	112	32
65 (siliceous gravel)	109	33	110	33	110	33	108	34
66 (limestone gravel)	107	35	108	35	109	34	108	35
67 (limestone gravel)	105	34	107	33	108	33	106	34
68 (siliceous gravel)	108	33	110	32	110	32	110	32
69 (slag)	65	43	67	41	66	42	68	40
70 (slag)	74	43	76	41	77	40	78	40
71 (slag)	82	42	83	42	83	42	85	40
72 (shell limestone)	90	42	90	42	90	42	89	42

[1] First shipment of material.
[2] Second shipment of material.

TABLE 5.—*Water-cement ratio, cement factor and strength tests—general average of all mixes and all grading*[1]

Aggregate No.	W/C	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. inch	*Lbs. per sq. inch*	*Lbs. per sq. inch*
40 (trap)	0.85	6.08	525	220	2,850
44 (siliceous gravel)	.84	5.53	475	195	2,860
46 (siliceous limestone)	.86	5.99	590	235	2,940
50 (siliceous gravel)	.85	5.63	530	215	2,980
60 (granite)	.88	5.84	520	225	3,020
61 (sandstone)	1.08	5.73	530	235	3,470
62 (cherty limestone)	.88	5.91	590	235	2,940
63 (argillaceous limestone)	1.01	5.92	495	240	3,140
64 (siliceous gravel)	.85	5.63	465	190	2,920
65 (siliceous gravel)	.83	5.64	495	195	2,860
66 (limestone gravel)	.86	5.69	585	250	3,310
67 (limestone gravel)	.89	5.68	580	250	3,300
68 (siliceous gravel)	.84	5.61	525	210	2,920
72 (shell limestone)	.96	5.95	550	255	3,140

[1] Flexure and tension specimens broken at 29 days, compression specimens broken at 33 days.

steel rod, bullet-shaped on the end. The sides were then spaded and the top struck off with a wooden float, the final finishing being done with a steel float. In making the tension cylinders the concrete was placed in three layers, each layer being rodded about thirty times with the same rod. Due to the limited facilities for handling the large number of specimens involved it was found necessary to keep them in moist air for 28 days after 1 day in the molds, so that the age at test was 29 days instead of the conventional 28 days.

The beams were tested with a portable cantilever device with an extension arm and dynamometer for applying the load. A view of this machine is shown in Figure 1. (*Figure 1 omitted*). The dynamometer was fastened directly to the extension arm so that no friction due to pulleys was included in the measured load. Two breaks were made on each beam. The tension cylinders were broken in a 100,000-pound Universal testing machine equipped with a hand wheel for slow application of load. A set of grips similar to those designed in the research laboratory of the Portland Cement Association was used for gripping the specimens. They may be briefly described as two pieces of 6-inch steel pipe lined with leather and split part way along four elements so as to slip over the ends of a straight cylindrical concrete specimen. The segments are drawn tight on the specimen by means of tangential bolts, thus developing enough friction between concrete and leather to prevent slipping during the test. Bolts passing through the head of each grip are provided with ball and socket joints both in the grip and at the centering plate on the testing machine, thus making the specimen and grips self aligning. A view of the device is shown in Figure 2. (*Omitted*).

Remnants from the tension specimens were capped with a neat cement paste made with a calcium chloride solution and broken in compression at 33 days. They varied in height and a correction factor was applied to make the ultimate load correspond to a specimen having a height twice its diameter. Results were therefore obtained in flexure and tension on the same batch of concrete cured in exactly the same manner while results were also obtained in tension and compression on exactly the same specimen but tested at slightly different ages.

Results Show Water-Cement Ratio not the only Factor Affecting Strength

Figure 3 gives the average results of all strength tests for all aggregates except the three slags. They were omitted because they were not included in mixes No. 2 and No. 4 (1:1.6:4 and 1:2:4½) and naturally could not be included in these grand averages. This same information, together with the corresponding water-cement ratios and cement factors, is given in Table 5. The unit values for the tensile strength and modulus of rupture were calculated to the nearest pound. These figures were carried through to the final averages. In the tables, however, the unit values are given to the nearest 5 pounds. The water-cement ratios reported in this and other tables were based on the total amounts of water added to each batch without correction for absorption of aggregates.

The modulus of rupture curve in Figure 3 shows that the aggregates arrange themselves in three general groups. For the purpose of discussion those show-

ing a modulus of rupture of more than 550 pounds per square inch have been placed in the first group, those between 550 and 500 in the second group, and those less than 500 in the third group. In the first group there are four aggregates, Nos. 46, 62, 66 and 67 (one siliceous limestone, one cherty limestone, and two limestone gravels), with but 10 pounds per square inch difference among them. In the second group there are six aggregates, Nos. 40, 50, 60, 61, 68 and 72 (one each of trap, granite, sandstone, shell limestone, and two siliceous gravels), while in the third or low group are four aggregates, Nos. 44, 63, 64, and 65 (three siliceous gravels and one argillaceous limestone). Figure 4 shows how the average strengths in tension, compression, and bending for each aggregate vary from the average for all aggregates. The highest value for modulus of rupture exceeds the lowest value by 27 per cent. A question naturally arises as to the reason for this difference, and it is explained by a consideration of such factors as water content, absorption, angularity of particles, and structural soundness of the aggregates. Since all of the concrete was made to the same consistency and the proportions and gradation for a given condition were constant, the amount of water used depended to a large extent upon the shape and absorption of the aggregates.

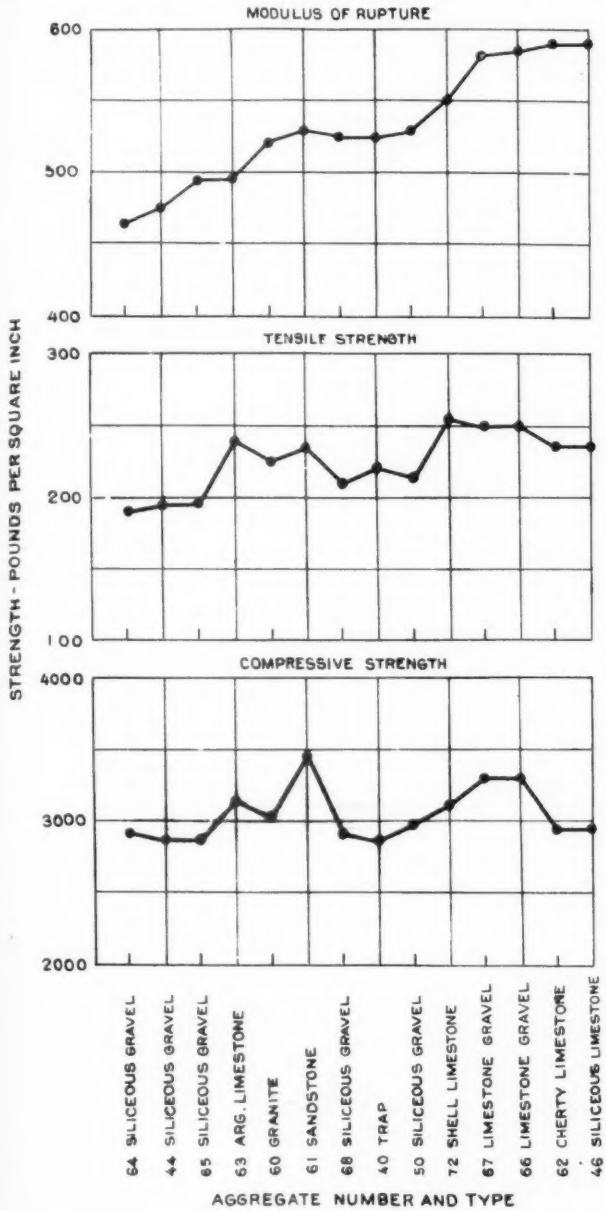

FIGURE 3.—AVERAGE STRENGTH TESTS FOR ALL MIXES AND ALL GRADINGS

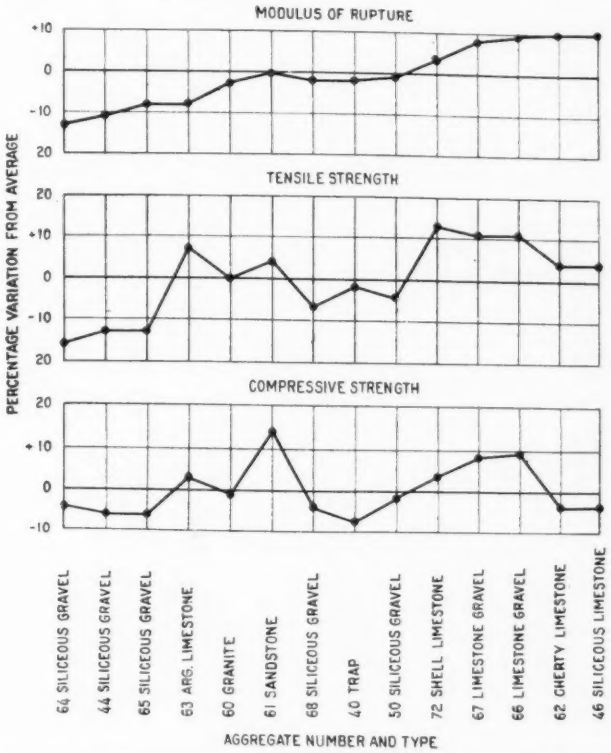

FIGURE 4.—VARIATION IN STRENGTH OF EACH AGGREGATE FROM THE GENERAL AVERAGE FOR ALL AGGREGATES, EXCEPT SLAG

We may assume first, that, other factors remaining the same, the amount of mixing water or the water-cement ratio used would be the cause of this difference. Comparing the siliceous gravel aggregate No. 64 with

a water-cement ratio of 0.85 and an absorption of 0.50 per cent with the siliceous limestone aggregate No. 46 with a water-cement ratio of 0.86 and an absorption of 0.04 per cent, we would expect the siliceous gravel to absorb a considerable amount of water, while the siliceous limestone would not, thereby lowering the net water-cement ratio in the case of the siliceous gravel. Under these circumstances the siliceous gravel should give the higher flexural strength, but on the contrary the siliceous limestone gave a strength 27 per cent higher than the siliceous gravel. Following the same line of thought, the siliceous gravel (No. 64) should give higher strengths than a number of the other materials, but reference to the data will show that this is not the case. Comparing other aggregates on the same basis will show that in so far as this investigation is concerned the water-cement ratio is not the only factor which controls the strength.

Considering next the angularity of the particles of the coarse aggregate, we see from Table 2 that the siliceous limestone and cherty limestone aggregates in the high group designated as Nos. 46 and 62, consisted entirely of crushed particles, while the limestone gravel designated as No. 66 had from 33 to 39 per cent crushed and No. 67, a limestone gravel, had from 67 to 92 per cent, depending upon the particular gradation considered. The two limestone gravels differ from the two limestones mentioned first in that they are crushed gravels and have some surfaces rounded, while the limestones are 100 per cent crushed. In the low group, the siliceous gravels, Nos. 44 and 64 both had a very low percentage of crushed material, although the siliceous gravel, No. 65, also of the low group, had a greater percentage than the limestone gravel, No. 66, in the high group. The trap, siliceous limestone, and granite (Nos. 40, 46, and 60), all had 100 per cent crushed material, but this siliceous limestone showed a strength about 13 per cent higher than the other two.

Mineral Composition of Aggregate Found to be Important

Since these facts do not explain the strength variations described let us examine the physical characteristics of the coarse aggregates still further. Taking first the high group, we see from Table 3 that No. 46 is a siliceous limestone, No. 62 is a cherty limestone, No. 66 is a cherty dolomitic crushed gravel, and No. 67 is a crushed limestone gravel with some chert. Two of these materials are crushed stones, one is a crushed gravel with about one-third crushed pieces, and the fourth is a gravel with about three-fourths crushed pieces. All of these materials are from different sources, two of them falling into the general class of crushed stone aggregates and two into the general class of gravel aggregates. From a mineralogical standpoint, however, they are practically the same, all four being essentially calcareous.

Considering the low group, we find Nos. 44 and 65 are essentially quartz gravels, while No. 64 is a gravel composed mostly of gneiss and quartz. No. 63 is an entirely different material, being a soft argillaceous limestone. This particular material was of two varieties and varied considerably throughout the series. The quartz gravels, Nos. 50 and 68, may be placed in the same mineral group with Nos. 44 and 65, but they show a considerably higher flexural strength and were placed in the intermediate strength group. Since in the material found in any one of these aggregates weathering may have progressed farther than in similar material in another, we might expect a difference in structural soundness which would affect the flexural strength.

Of the aggregates in the intermediate group, No. 40 is a very hard and heavy trap rock; No. 60 is a sound granite; No. 61 is a very soft sandstone, practically every piece of which fractured in the flexure tests; No. 68 is a material somewhat similar to No. 50, but from an entirely different source; and No. 72 is a shell limestone containing many soft pieces but which gave much higher strength than any other aggregate listed in the intermediate group.

Considering all factors, the tests clearly indicate that the mineral composition of the coarse aggregate is of prime importance and must be considered along with other factors when the question of resistance to bending arises.

Referring again to Figure 3 and Table 5, and examining the tensile strength values, we find a difference of 34 per cent between the highest and lowest results. In this particular case the shell limestone aggregate No. 72 shows the highest value, with the limestone gravel aggregates Nos. 66 and 67 only slightly lower. It will be remembered that the latter two aggregates showed very high strength in the flexure tests. The siliceous limestone, cherty limestone, sandstone and argillaceous limestone (Nos. 46, 62, 61, and 63) also show high tensile strength. In fact, the difference among eight aggregates, beginning with No. 68 at 210 pounds per square inch and ending with No. 63 at 240 pounds per square inch is very slight. However, the values are rather small, which makes the percentage variations large. There is a distinctive low group composed of three siliceous gravels (Nos. 64, 44 and

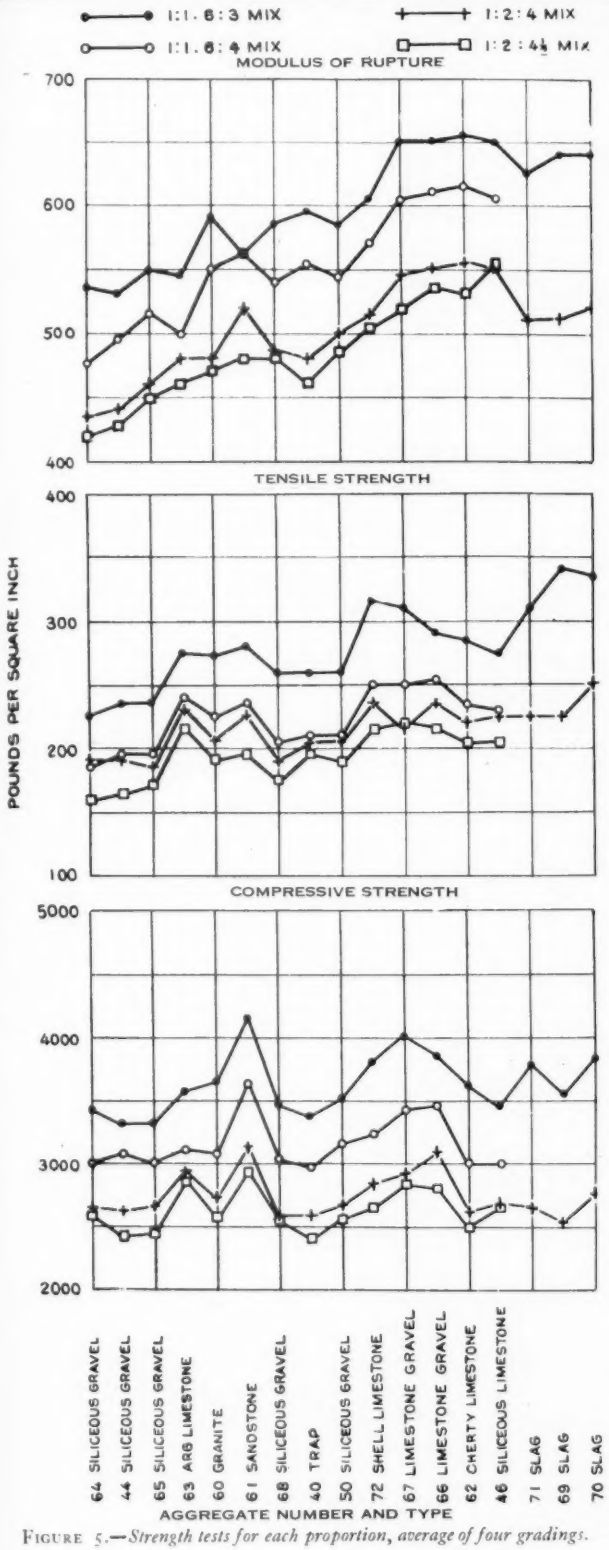

FIGURE 5.—*Strength tests for each proportion, average of four gradings.*

65), the same aggregates showing low flexural strength. It is readily apparent that the aggregates do not arrange themselves in exactly the same order in tensile strength that they do in flexure, the main difference occurring in the soft sandstone and limestone aggregates, Nos. 61, 63 and 72, which show a higher relative strength with respect to the other aggregates in tension than in flexure.

In the compressive tests also shown in Figure 3 and Table 5, we see that with the exception of the sandstone and two limestone gravels, Nos. 61, 66 and 67, the average crushing strength runs fairly close to 3,000 pounds per square inch for all aggregates. Comparing the compression curve with that for flexure and tension shows that the two limestone gravel aggregates Nos. 66 and 67 are outstandingly high for all three types of test, while three of the siliceous gravels Nos. 44, 64, and 65 are low in all cases. For the balance of the materials, however, there appears to be no consistent relation between compression and either modulus of rupture or direct tension. These values in general show the fallacy of attempting to use direct ratios between compression, tension and flexure in a general way, and without taking into account the particular material at hand.

Proceeding now to Figure 5, we shall examine the strength values for each mix, individually and collectively. These data, as well as the corresponding water-cement ratios and cement factors for each mix, are given in detail in Table 6.

In Figure 5, the three slag aggregates, Nos. 69, 70, and 71, are included for the 1:1.6:3 and 1:2:4 mixes. It will be observed that each of the three slags shows relatively high values for modulus of rupture for the 1:1.6:3 mix, but that the corresponding values for 1:2:4 mix are somewhat low as compared to the calcareous materials comprising the high-strength group. Examining the four modulus of rupture curves collectively we see that in general they are parallel, the greatest discrepancy being sandstone aggregate No. 61, which shows quite erratic results. It is also interesting to note from the graphs that the curves for the 1:1.6:3 and 1:1.6:4 mixes dip down in the case of the argillaceous limestone aggregate No. 63, while for the two leaner mixes they go up. For the trap aggregate No. 40, the curves dip down for the leaner mixes, while they go up for the richer ones. Considering the two materials, No. 40 is a very hard trap rock which we would naturally expect to show to better advantage in a rich mix, while No. 63, being a softer material, the opposite is of course true. Note also the relatively

high strengths for the granite aggregate No. 60 in the two richer mixes.

TABLE 6.—*Average water-cement ratio, cement factor, and results of strength tests (includes four gradings) of all mixes*[1]

1:1.6:3 MIX

Aggregate No.	$\frac{W}{C}$	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*
40 (trap)	0.75	7.08	595	260	3,390
44 (siliceous gravel)	.74	6.49	530	235	3,320
46 (siliceous limestone)	.75	6.97	610	275	3,450
50 (gravel)	.75	6.59	585	260	3,520
60 (granite)	.76	6.80	590	275	3,650
61 (sandstone)?	.93	6.71	560	280	4,150
62 (cherty limestone)	.76	6.50	655	285	3,610
63 (argillaceous limestone)	.87	6.92	545	275	3,590
64 (gravel)	.75	6.57	535	225	3,420
65 (gravel)	.74	6.57	550	235	3,320
66 (gravel)	.75	6.68	630	290	3,850
67 (gravel limestone)	.78	6.69	670	310	4,010
68 (gravel)	.74	6.57	585	260	3,460
69 (slag)	.86	7.17	640	340	3,570
70 (slag)	.81	7.08	640	335	3,850
71 (slag)	.80	7.11	625	310	3,780
72 (shell limestone)	.83	6.94	605	315	3,810
1:1.6:4 MIX					
40 (trap)	0.81	6.16	555	210	2,980
44 (siliceous gravel)	.79	5.54	495	195	3,070
46 (siliceous limestone)	.81	6.03	605	230	3,000
50 (siliceous gravel)	.80	5.69	545	210	3,150
60 (granite)	.83	5.92	550	225	3,080
61 (sandstone)	1.04	5.81	560	235	3,650
62 (cherty limestone)	.83	5.97	615	235	3,000
63 (argillaceous limestone)	.98	5.98	500	240	3,130
64 (siliceous gravel)	.80	5.68	475	185	3,020
65 (siliceous gravel)	.78	5.69	515	195	3,010
66 (limestone gravel)	.81	5.75	610	255	3,460
67 (limestone gravel)	.85	5.74	605	250	3,430
68 (siliceous gravel)	.80	5.65	540	205	3,030
72 (shell limestone)	.92	6.06	570	250	3,250
1:2:4 MIX					
40 (trap)	0.91	5.74	480	205	2,590
44 (siliceous gravel)	.90	5.22	440	190	2,630
46 (siliceous limestone)	.92	5.64	550	225	2,680
50 (siliceous gravel)	.91	5.31	500	205	2,680
60 (granite)	.94	5.51	480	205	2,740
61 (sandstone)	1.15	5.40	520	225	3,140
62 (cherty limestone)	.95	5.56	555	220	2,620
63 (argillaceous limestone)	1.07	5.58	480	230	2,940
64 (siliceous gravel)	.91	5.30	435	190	2,650
65 (siliceous gravel)	.88	5.29	460	185	2,660
66 (limestone gravel)	.92	5.35	550	235	3,100
67 (limestone gravel)	.95	5.33	545	215	2,930
68 (siliceous gravel)	.91	5.27	485	190	2,600
69 (slag)	1.09	5.71	510	225	2,540
70 (slag)	1.02	5.70	520	250	2,790
71 (slag)	1.00	5.72	510	225	2,660
72 (shell limestone)	1.03	5.57	515	235	2,850
1:2:4½ MIX					
40 (trap)	0.94	5.36	460	195	2,430
44 (siliceous gravel)	.91	4.86	430	165	2,430
46 (siliceous limestone)	.94	5.27	555	205	2,650
50 (siliceous gravel)	.94	4.94	485	190	2,570
60 (granite)	.97	5.12	470	190	2,590
61 (sandstone)	1.21	5.01	480	195	2,930
62 (cherty limestone)	.96	5.21	530	205	2,520
63 (argillaceous limestone)	1.11	5.21	460	215	2,880
64 (siliceous gravel)	.93	4.94	420	160	2,580
65 (siliceous gravel)	.91	4.99	450	170	2,450
66 (limestone gravel)	.94	4.98	535	215	2,820
67 (limestone gravel)	.99	4.97	520	220	2,840
68 (siliceous gravel)	.92	4.94	480	175	2,590
72 (shel. limestone)	1.06	5.24	505	215	2,660

[1] Flexure and tension specimens broken at 29 days, compression specimens broken at 33 days.

Results Indicate Desirability of Determining Concrete Making Properties of Aggregates

The relation between flexural strength and proportions as affected by either changes in the sand-cement ratio or the amount of coarse aggregate may also be studied by reference to Figure 5. For instance, using mix No. 3, 1:2:4, as the starting point, we find that increasing the amount of coarse aggregate to 4½ parts only slightly lowers the strength, the average difference in modulus of rupture being only 15 pounds per square inch. On the other hand, decreasing the sand to 1.6 parts (mix No. 2) and holding the coarse aggregate constant has a marked effect, the average increase for all aggregates being 50 pounds per square inch. Comparing the 1:1.6:3 and 1:1.6:4 mixes (Nos. 1 and 2) likewise shows that decreasing the coarse aggregate one part, with the sand held constant, still further increases the strength about 40 pounds per square inch. It is interesting to note, however, that the maximum variations in strength for a given mix due to type of aggregate is as great as the average difference in strength between the richest and leanest mixes used. The siliceous limestone aggregate No. 46, for instance, used in a 1:2:4½ mix, develops a somewhat higher strength than siliceous gravel aggregate No. 64 in the 1:1.6:3 mix. Reference to Table 6 shows that in the first case 5.27 bags of cement were used per cubic yard of concrete, whereas in the second case 6.57 bags were required. The economic possibilities resulting from a study of the concrete making properties of aggregates should be obvious to any one studying these data.

Referring now to the tensile strength curves in Figure 5, we note that the three slag aggregates are high in strength for the 1:1.6:3 mix while in the 1:2:4 mix, slag No. 70 shows the highest strength of all, with the other two slags, Nos. 69 and 71, in the high group. One noticeable difference between these curves and those for the flexure tests is that the greatest difference in tensile strength was found between the 1:1.6:3 and 1:1.6:4 mixes (Nos. 1 and 2) instead of between the 1:2:4 and 1:2:4½ mixes (Nos. 2 and 3). This is an indication that the tensile and flexural strength does not increase in exactly the same ratio as the mix is changed. This will be discussed more fully later.

In the compression curves in Figure 5, two of the slags, Nos. 70 and 71, are fairly high in strength in the 1:1.6:3 mix, while the other slag, No. 69, is slightly below the average. In the 1:2:4 mix, however, slag No. 70 is about the average, while Nos. 69 and 71 are below the average, showing a slight falling off in

strength for the slags in the leaner mix. In all mixes, the sandstone No. 61 is higher than any other aggregate, while the limestone gravels, Nos. 66 and 67, also show consistently high values. All four curves are practically parallel. In general, there is about the same difference in strength between the 1:1.6:3 and

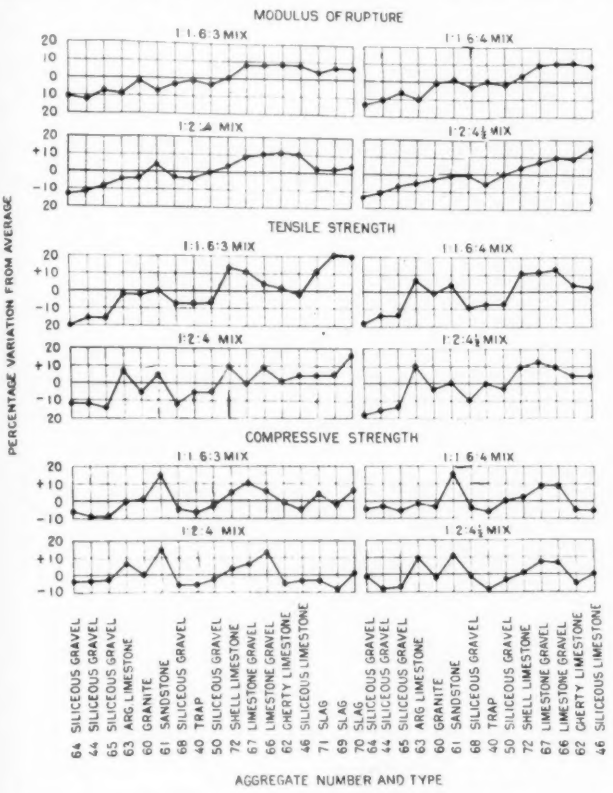

FIGURE 6.—VARIATIONS OF EACH AGGREGATE FROM THE GENERAL AVERAGE FOR EACH MIX

1:1.6:4 mixes as between the 1:1.6:4 and 1:2:4 mix, while the 1:2:4½ mix was close to the 1:2:4 mix, as was the case in tension and flexure.

Figure 6 shows the percentage variations from the average in tension, flexure and compression for each aggregate for each mix.

Figure 7 and Table 7 give the strength values for each individual grading, each value being the average for the four mixes. The modulus of rupture curves show no consistent difference in strength for variations in grading, although it is noticed that for the softer aggregates, Nos. 61, 63, and 72 (sandstone, argillaceous limestone, and shell limestone), grading No. 4 gave the lowest values. In most cases, gradings No. 1 or No. 2 were high in strength, while No. 3 or No. 4 were low, the most noticeable exception being limestone gravel aggregate No. 66, which gave a high value for grading No. 4, and low value for grading No. 2. In most cases, as for aggregates Nos. 44, 65, 67, and 68, the difference for all four gradings was so slight as to

TABLE 7.—*Water-cement ratio, cement factor and results of strength tests (on four mixes)*[1]

Aggregate No.	$\frac{W}{C}$	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. inch	*Lbs. per sq. inch*	*Lbs. per sq. inch*
GRADING NO. 1					
40 (trap)	0.82	6.13	515	210	2,830
44 (siliceous gravel)	.80	5.58	475	180	2,810
46 (siliceous limestone)	.82	6.04	595	210	2,900
50 (siliceous gravel)	.82	5.71	540	195	2,990
60 (granite)	.83	5.93	535	210	3,150
61 (sandstone)	1.03	5.82	535	240	3,530
62 (cherty limestone)	.83	6.00	595	230	3,000
63 (argillaceous limestone)	.96	6.02	520	240	3,280
64 (siliceous gravel)	.82	5.71	475	180	2,920
65 (siliceous gravel)	.81	5.68	490	175	2,770
66 (limestone gravel)	.83	5.75	590	240	3,370
67 (limestone gravel)	.85	5.76	585	225	3,210
68 (siliceous gravel)	.82	5.69	520	185	2,870
72 (shell limestone)	.90	6.05	565	240	3,200
GRADING NO. 2					
40 (trap)	0.84	6.14	540	220	2,900
44 (siliceous gravel)	.82	5.54	480	200	2,940
46 (siliceous limestone)	.83	6.04	595	235	3,110
50 (siliceous gravel)	.84	5.68	525	215	3,050
60 (granite)	.85	5.86	540	225	3,040
61 (sandstone)	1.06	5.79	535	235	3,620
62 (cherty limestone)	.85	5.90	595	240	3,080
63 (argillaceous limestone)	.98	5.98	505	240	3,220
64 (siliceous gravel)	.84	5.64	460	195	2,950
65 (siliceous gravel)	.82	5.62	505	200	2,870
66 (limestone gravel)	.84	5.69	565	245	3,240
67 (limestone gravel)	.87	5.68	585	250	3,430
68 (siliceous gravel)	.83	5.61	520	205	2,940
72 (shell limestone)	.93	5.96	555	260	3,280
GRADING NO. 3					
40 (trap)	0.87	6.04	520	215	2,870
44 (siliceous gravel)	.85	5.48	470	200	2,900
46 (siliceous limestone)	.86	5.98	575	240	2,930
50 (siliceous gravel)	.86	5.58	515	220	3,000
60 (granite)	.90	5.81	500	220	3,030
61 (sandstone)	1.10	5.69	540	230	3,460
62 (cherty limestone)	.89	5.87	575	235	2,950
63 (argillaceous limestone)	1.01	5.92	490	245	3,150
64 (siliceous gravel)	.85	5.62	470	185	2,960
65 (siliceous gravel)	.84	5.61	490	195	2,990
66 (limestone gravel)	.88	5.65	575	255	3,360
67 (limestone gravel)	.91	5.64	575	260	3,330
68 (siliceous gravel)	.85	5.56	530	215	2,970
72 (shell limestone)	.98	5.93	550	260	3,090
GRADING NO. 4					
40 (trap)	0.90	6.03	515	225	2,780
44 (siliceous gravel)	.87	5.51	475	210	2,810
46 (siliceous limestone)	.90	5.89	600	250	2,850
50 (siliceous gravel)	.89	5.57	535	235	2,880
60 (granite)	.93	5.76	515	240	2,840
61 (sandstone)	1.14	5.63	505	235	3,260
62 (cherty limestone)	.94	5.86	585	240	2,720
63 (argillaceous limestone)	1.07	5.76	475	235	2,900
64 (siliceous gravel)	.88	5.53	455	195	2,830
65 (siliceous gravel)	.86	5.64	495	215	2,820
66 (limestone gravel)	.88	5.67	620	260	3,270
67 (limestone gravel)	.93	5.66	570	265	3,240
68 (siliceous gravel)	.87	5.56	525	225	2,910
72 (shell limestone)	1.02	5.88	530	255	3,010

[1] Flexure and tension specimens broken at 29 days, compression specimens broken at 33 days.

indicate that within the ranges used in this investigation the grading of the coarse aggregate has little direct effect upon flexural strength.

In the tensile-strength tests, grading No. 1 resulted in low values in all but two cases, while grading No. 4 usually gave the highest values. One possible explanation for this is the relation between the size of the cross section of the specimen and the maximum size of aggregate used. In grading No. 1, 60 per cent of the material was retained on the 1¼-inch screen. The tension specimens had approximately 6-inch circular cross sections and it is believed that a larger cross section would probably have given higher strengths for the coarser gradings. One of the conclusions reached by Gonnerman and Shuman in their paper, Compression, Flexural and Tension Tests of Plain Concrete,[1] was that the size of specimen did not affect the tensile strength. However, it must be remembered that in their work the maximum size of aggregate was 1½ inches. The fact that grading No. 4, which had no particles greater than 1¼-inch, gave the highest values in tension but did not do so in flexure or compression is an indication that variations in grading possibly affect the tensile strength to a greater extent than they affect the flexural or compressive strength.

No Relation Found Between Results of Abrasion Test and Strength of Concrete

On examination of the compressive strength curves in Figure 7 we note just the opposite effect; that is, grading No. 4 shows low values generally while grading No. 2 is high in strength. Taking into account the fact that the compression tests were made on the broken tension pieces, the results give indications that, from the standpoint of strength, changing the grading may produce opposite results in different types of tests.

A more detailed study of the strength values may be made by referring to Table 8. In this table the water-cement ratios, cement factors, and the results of the three types of strength tests are shown for each grading and each mix separately.

The results of abrasion tests on each of the coarse aggregates are given in Table 2, together with a notation in each case, indicating the particular type of abrasion test made. In Figure 8 these values have been plotted against the results of the three strength tests, for the purpose of ascertaining if any relation exists. It may be concluded from this chart that, within the range of quality here considered, no relation exists between the quality of the coarse aggregate as measured by this test and the strength of the concrete.

[1] Proceedings of A. S. T. M., vol. 28, pt. 2, p. 551.

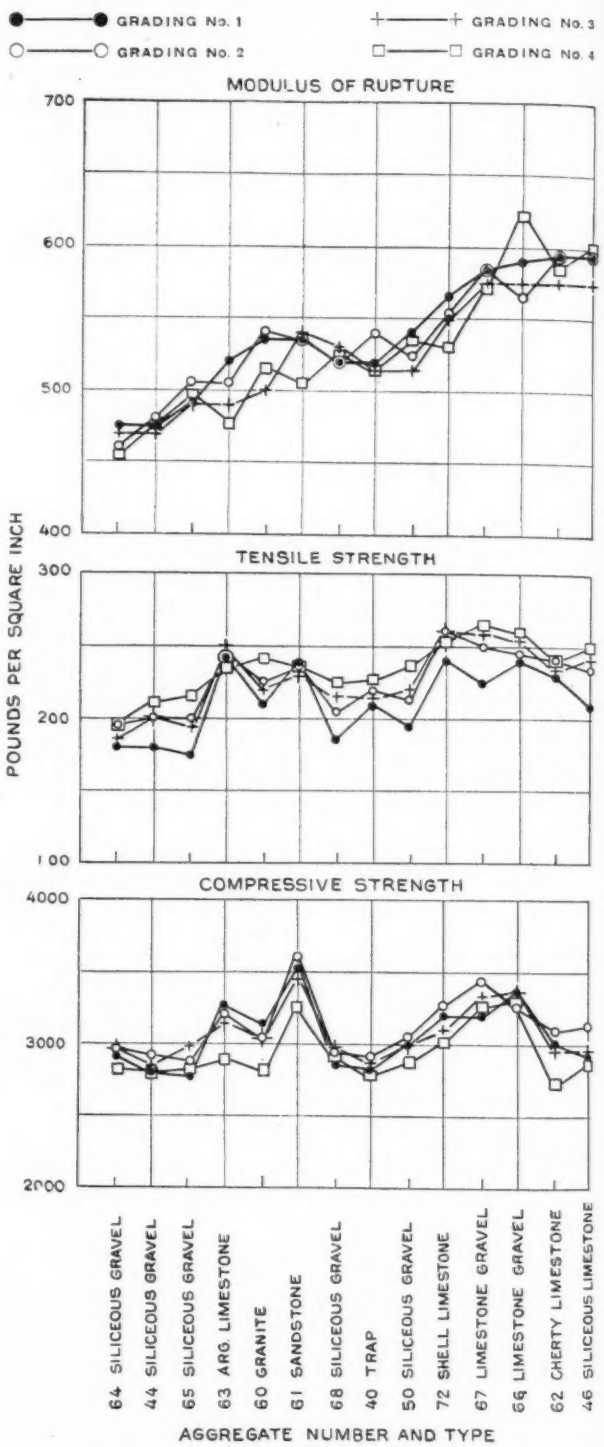

FIGURE 7.—RESULTS OF STRENGTH TESTS ON EACH GRADING. AVERAGE FOR FOUR MIXES

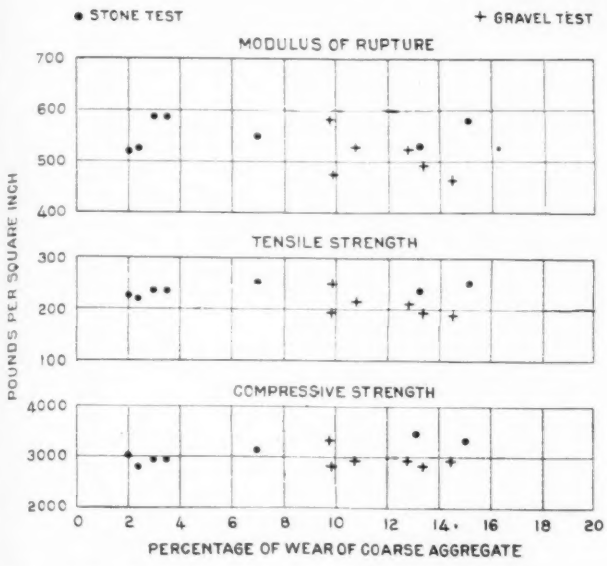

FIGURE 8.—RELATION BETWEEN STRENGTH OF CONCRETE AND PERCENTAGE OF WEAR OF COARSE AGGREGATE

Relation Between Type of Aggregate and Yield Studied

The amount of cement required to produce a cubic yard of concrete for each of the aggregates and proportions studied is plotted in Figure 9. In this graph the aggregates are plotted in the order of ascending flexural strength as in Figure 3. The effect of shape of coarse aggregate fragment on yield is very apparent.

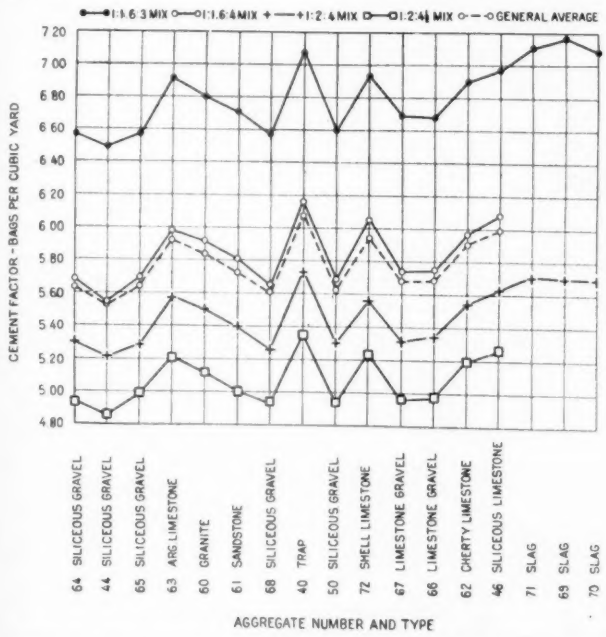

FIGURE 9.—QUANTITY OF CEMENT REQUIRED FOR 1 CUBIC YARD OF CONCRETE. AGGREGATES ARRANGED IN ASCENDING ORDER OF FLEXURAL STRENGTH

It will be noted that the gravel aggregates Nos. 64, 44, 50, 65, 68, 67, and 66, all of which contain rounded fragments show consistently higher yields or lower cement factors than any of the aggregates consisting of crushed fragments. This of course is merely the effect of variations in void content due to shape of

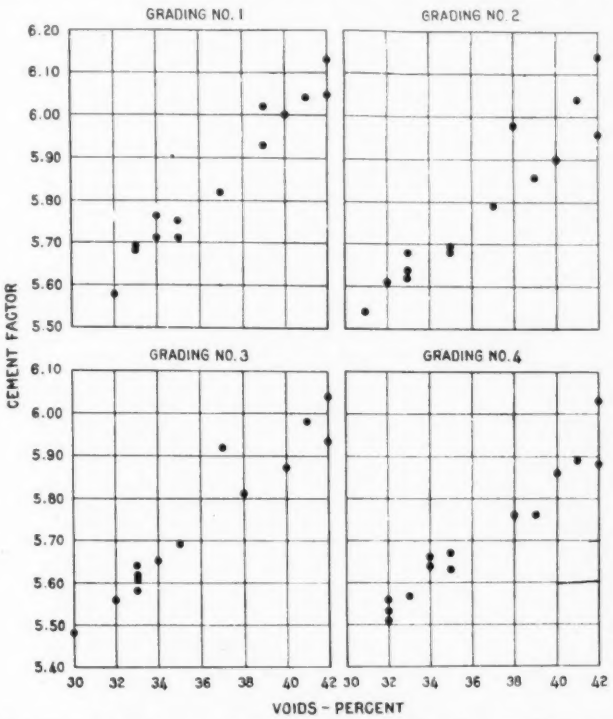

FIGURE 10.—RELATION BETWEEN CEMENT FACTOR AND VOIDS IN COARSE AGGREGATE, AVERAGE OF FOUR MIXES

particles as is very clearly brought out by reference to Figure 10, where the relation between cement factor and percentage of voids for each grading is shown. It will be noted that there is a maximum variation of 12 per cent in voids for 14 of the 17 types comprised in this study. This occurs for grading No. 3 and caused a maximum variation in the cement factor of 0.56 bags of cement. (See Table 7). These values illustrate the effect of shape of aggregate fragment on yield when the proportioning is done by the usual volumetric method.

The effect of grading of coarse aggregate on yield for each type of aggregate may be studied by reference to Table 7. It will be observed that grading No. 1, in general, requires somewhat more cement than the others. However, the maximum variation in cement

TABLE 8.—*Water-cement ratio, cement factor, and results of strength tests*[1]

1:1.6:3 MIX, GRADING NO. 1

Aggregate No.	$\frac{W}{C}$	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*
40 (trap)	0.72	7.15	570	255	3,280
44 (siliceous gravel)	.71	6.52	520	210	3,160
46 (siliceous limestone)	.72	7.00	675	245	3,180
50 (siliceous gravel)	.73	6.60	590	230	3,460
60 (granite)	.73	6.91	605	200	3,750
61 (sandstone)	.90	6.82	550	270	3,990
62 (cherty limestone)	.73	6.98	655	280	3,710
63 (argillaceous limestone)	.84	7.08	560	255	3,650
64 (siliceous gravel)	.73	6.65	560	205	3,390
65 (siliceous gravel)	.73	6.57	530	220	3,370
66 (limestone gravel)	.74	6.71	645	265	3,910
67 (limestone gravel)	.76	6.74	655	285	3,900
68 (siliceous gravel)	.73	6.68	570	230	3,340
69 (slag)	.82	7.31	655	310	3,440
70 (slag)	.77	7.23	640	305	3,930
71 (slag)	.77	7.21	645	280	3,640
72 (shell limestone)	.77	7.05	610	305	3,950

1:1.6:3 MIX, GRADING NO. 2

40 (trap)	0.74	7.15	615	270	3,460
44 (siliceous gravel)	.73	6.50	540	250	3,370
46 (siliceous limestone)	.73	7.03	645	275	3,630
50 (siliceous gravel)	.74	6.65	580	250	3,540
60 (granite)	.74	6.80	620	280	3,640
61 (sandstone)	.92	6.74	540	270	4,150
62 (cherty limestone)	.74	6.90	680	290	3,700
63 (argillaceous limestone)	.85	6.93	545	275	3,640
64 (siliceous gravel)	.74	6.59	520	230	3,390
65 (siliceous gravel)	.72	6.59	560	250	3,170
66 (limestone gravel)	.74	6.68	625	285	3,700
67 (limestone gravel)	.76	6.70	670	310	4,120
68 (siliceous grave)	.73	6.59	610	255	3,430
69 (slag)	.86	7.12	635	345	3,490
70 (slag)	.79	7.15	650	330	3,860
71 (slag)	.78	7.10	615	325	3,970
72 (shell limestone)	.82	6.93	630	320	3,840

1:1.6:3 MIX, GRADING NO. 3

40 (trap)	0.76	6.93	610	255	3,500
44 (siliceous gravel)	.75	6.45	530	235	3,350
46 (siliceous limestone)	.75	6.97	640	285	3,480
50 (siliceous gravel)	.75	6.55	590	285	3,570
60 (granite)	.77	6.76	570	275	3,710
61 (sandstone)	.93	6.69	580	275	4,270
62 (cherty limestone)	.77	6.85	625	275	3,530
63 (argillaceous limestone)	.87	6.93	545	245	3,610
64 (siliceous gravel)	.76	6.54	530	220	3,330
65 (siliceous gravel)	.74	6.53	550	210	3,410
66 (limestone gravel)	.75	6.62	635	300	3,860
67 (limestone gravel)	.80	6.65	655	315	4,110
68 (siliceous gravel)	.74	6.49	595	235	3,520
69 (slag)	.87	7.15	645	355	3,710
70 (slag)	.82	7.03	650	345	3,880
71 (slag)	.81	7.05	630	310	3,820
72 (shell limestone)	.83	6.93	615	310	3,780

1:1.6:3 MIX, GRADING NO. 4

40 (trap)	0.78	7.03	590	235	3,330
44 (siliceous gravel)	.76	6.50	540	250	3,410
46 (siliceous limestone)	.74	6.88	650	300	3,510
50 (siliceous gravel)	.77	6.53	570	275	3,520
60 (granite)	.81	6.74	555	240	3,480
61 (sandstone)	.95	6.57	570	290	4,190
62 (cherty limestone)	.80	6.87	655	300	3,480
63 (argillaceous limestone)	.91	6.74	525	285	3,470
64 (siliceous gravel)	.77	6.51	525	235	3,520
65 (siliceous gravel)	.76	6.59	555	255	3,340
66 (limestone gravel)	.77	6.73	700	315	3,920
67 (limestone gravel)	.81	6.68	615	330	3,910
68 (siliceous gravel)	.75	6.50	570	285	3,540
69 (slag)	.91	7.09	635	345	3,630
70 (slag)	.83	6.91	635	355	3,730
71 (slag)	.85	7.05	615	315	3,690
72 (shell limestone)	.88	6.83	575	330	3,650

[1] Flexure and tension specimens broken at 29 days, compression specimens broken at 33 days.

1:1.6:4 MIX, GRADING NO. 1

Aggregate No.	$\frac{W}{C}$	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*
40 (trap)	0.78	6.21	570	200	2,950
44 (siliceous gravel)	.75	5.58	510	185	3,000
46 (siliceous l mestone)	.78	6.13	620	230	3,100
50 (siliceous gravel)	.77	5.80	570	190	3,210
60 (granite)	.78	6.01	530	215	3,270
61 (sandstone)	.99	5.89	565	240	3,860
62 (cherty limestone)	.77	6.04	625	225	3,050
63 (argillaceous limestone)	.92	6.10	525	250	3,220
64 (siliceous gravel)	.77	5.77	485	180	2,930
65 (siliceous grave)	.75	5.73	515	165	2,860
66 (limestone gravel)	.77	5.81	635	255	3,420
67 (limestone gravel)	.81	5.83	610	225	3,180
68 (siliceous gravel)	.77	5.72	540	175	2,820
72 (shell limestone)	.86	6.14	590	235	3,200

1:1.6:4 MIX, GRADING NO. 2

40 (trap)	0.79	6.23	595	225	3,010
44 (siliceous gravel)	.76	5.57	490	205	3,170
46 (siliceous limestone)	.79	6.13	575	230	3,140
50 (siliceous gravel)	.79	5.77	540	215	3,290
60 (granite)	.82	5.98	590	230	3,000
61 (sandstone)	1.01	5.87	590	250	3,890
62 (cherty limestone)	.79	6.01	600	235	3,260
63 (argillaceous limestone)	.95	6.05	525	240	3,380
64 (siliceous gravel)	.78	5.70	470	195	3,140
65 (siliceous gravel)	.77	5.67	495	200	3,080
66 (limestone gravel)	.78	5.75	580	265	3,370
67 (limestone gravel)	.83	5.74	595	245	3,670
68 (siliceous gravel)	.78	5.66	520	200	3,180
72 (shell limestone)	.88	6.00	555	265	3,540

1:1.6:4 MIX, GRADING NO. 3

40 (trap)	0.82	6.14	525	195	3,070
44 (siliceous gravel)	.81	5.49	485	185	3,080
46 (siliceous limestone)	.82	6.08	580	220	2,940
50 (siliceous gravel)	.81	5.61	510	210	3,130
60 (granite)	.85	5.89	520	210	3,130
61 (sandstone)	1.06	5.77	555	240	3,450
62 (cherty limestone)	.84	5.95	625	250	3,180
63 (argillaceous limestone)	.99	5.95	485	240	3,140
64 (siliceous gravel)	.80	5.66	485	175	3,210
65 (siliceous gravel)	.79	5.65	515	215	3,170
66 (limestone gravel)	.84	5.73	590	250	3,520
67 (limestone gravel)	.87	5.68	600	275	3,470
68 (siliceous gravel)	.81	5.60	540	220	3,080
72 (shell limestone)	.95	6.08	585	250	3,160

1:1.6:4 MIX, GRADING NO 4

40 (trap)	0.86	6.05	535	210	2,890
44 (siliceous gravel)	.82	5.52	495	210	3,010
46 (siliceous limestone)	.86	5.98	635	240	2,810
50 (siliceous gravel)	.84	5.60	565	225	2,950
60 (granite)	.88	5.80	555	250	2,900
61 (sandstone)	1.11	5.71	520	225	3,400
62 (cherty limestone)	.90	5.89	615	225	2,510
63 (argillaceous limestone)	1.05	5.80	475	235	2,800
64 (siliceous gravel)	.84	5.59	465	195	2,810
65 (siliceous gravel)	.81	5.72	540	205	2,940
66 (limestone gravel)	.85	5.71	640	260	3,340
67 (limestone gravel)	.89	5.71	615	260	3,420
68 (siliceous gravel)	.83	5.63	565	220	3,050
72 (shell limestone)	.97	6.01	555	255	3,120

1:2:4 MIX, GRADING NO. 1

40 (trap)	0.87	5.76	475	205	2,750
44 (siliceous gravel)	.85	5.30	455	160	2,560
46 (siliceous limestone)	.87	5.72	560	205	2,850
50 (siliceous gravel)	.87	5.42	510	190	2,750
60 (granite)	.88	5.62	495	185	2,940
61 (sandstone)	1.10	5.48	540	230	3,160
62 (cherty limestone)	.89	5.72	545	220	2,690
63 (argillaceous limestone)	1.02	5.64	510	235	3,100
64 (siliceous gravel)	.87	5.42	430	185	2,840
65 (siliceous gravel)	.86	5.35	460	165	2,570
66 (limestone gravel)	.89	5.44	570	225	3,260
67 (limestone gravel)	.91	5.40	530	190	2,990
68 (siliceous gravel)	.88	5.37	480	165	2,600
69 (slag)	1.04	5.68	490	210	2,440
70 (slag)	.98	5.77	500	230	2,670
71 (slag)	.97	5.75	500	220	2,660
72 (shell limestone)	.98	5.71	520	210	2,960

TABLE 8.—*Water-cement ratio, cement factor, and results of strength tests*—Continued

1:2:4 MIX, GRADING NO. 2

Aggregate No.	$\frac{W}{C}$	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*
40 (trap)	0.89	5.77	495	195	2,640
44 (siliceous gravel)	.88	5.23	430	185	2,770
46 (siliceous limestone)	.91	5.69	555	215	2,710
50 (siliceous gravel)	.91	5.31	485	215	2,780
60 (granite)	.91	5.53	470	200	2,890
61 (sandstone)	1.14	5.46	535	230	3,320
62 (cherty limestone)	.93	5.50	570	205	2,740
63 (argillaceous limestone)	1.04	5.62	485	235	2,990
64 (siliceous gravel)	.90	5.30	445	195	2,660
65 (siliceous gravel)	.88	5.30	490	195	2,690
66 (limestone gravel)	.92	5.35	535	220	3,050
67 (limestone gravel)	.93	5.34	575	205	2,980
68 (siliceous gravel)	.89	5.26	480	195	2,750
69 (slag)	1.07	5.69	515	230	2,630
70 (slag)	.99	5.72	555	255	3,160
71 (slag)	.99	5.73	520	205	2,700
72 (shell limestone)	1.00	5.65	520	240	2,940

1:2:4 MIX, GRADING NO. 3

40 (trap)	0.93	5.72	475	205	2,500
44 (siliceous gravel)	.90	5.16	435	185	2,610
46 (siliceous limestone)	.94	5.62	540	235	2,580
50 (siliceous gravel)	.91	5.26	480	195	2,660
60 (granite)	.97	5.46	480	210	2,660
61 (sandstone)	1.16	5.36	540	225	3,230
62 (cherty limestone)	.96	5.52	555	220	2,580
63 (argillaceous limestone)	1.07	5.57	465	225	3,020
64 (siliceous gravel)	.91	5.31	430	185	2,510
65 (siliceous gravel)	.89	5.26	450	180	2,730
66 (limestone gravel)	.92	5.32	550	235	3,090
67 (limestone gravel)	.96	5.28	530	230	2,950
68 (siliceous gravel)	.92	5.23	500	190	2,540
69 (slag)	1.10	5.76	535	230	2,520
70 (slag)	1.03	5.67	515	250	2,710
71 (slag)	.98	5.75	525	245	2,760
72 (shell limestone)	1.05	5.51	515	250	2,790

1:2:4 MIX, GRADING NO. 4

40 (trap)	0.96	5.70	480	220	2,466
44 (siliceous gravel)	.94	5.17	435	215	2,550
46 (siliceous limestone)	.96	5.53	540	240	2,600
50 (siliceous gravel)	.95	5.26	520	225	2,540
60 (granite)	1.00	5.44	475	215	2,490
61 (sandstone)	1.20	5.28	470	225	2,830
62 (cherty limestone)	1.03	5.49	550	235	2,460
63 (argillaceous limestone)	1.13	5.47	460	225	2,660
64 (siliceous gravel)	.95	5.18	430	190	2,580
65 (siliceous gravel)	.91	5.27	440	205	2,670
66 (limestone gravel)	.94	5.31	555	260	3,010
67 (limestone gravel)	1.00	5.29	535	235	2,810
68 (siliceous gravel)	.95	5.22	470	215	2,530
69 (slag)	1.15	5.71	495	240	2,530
70 (slag)	1.07	5.65	510	255	2,620
71 (slag)	1.05	5.67	490	220	2,520
72 (shell limestone)	1.09	5.47	505	240	2,720

1:2:4½ MIX, GRADING NO. 1

40 (trap)	0.89	5.39	455	175	2,350
44 (siliceous gravel)	.87	4.90	425	155	2,500
46 (siliceous limestone)	.90	5.32	525	165	2,460
50 (siliceous gravel)	.90	5.02	490	170	2,550
60 (granite)	.91	5.19	500	175	2,650
61 (sandstone)	1.14	5.08	495	215	3,110
62 (cherty limestone)	.91	5.27	560	195	2,520
63 (argillaceous limestone)	1.07	5.27	480	215	3,170
64 (siliceous gravel)	.90	5.00	420	145	2,520
65 (siliceous gravel)	.88	5.05	455	150	2,290
66 (limestone gravel)	.90	5.05	505	210	2,870
67 (limestone gravel)	.93	5.05	545	210	2,790
68 (siliceous gravel)	.89	5.00	485	170	2,700
72 (shell limestone)	.98	5.31	535	215	2,680

TABLE 8.—*Water-cement ratio, cement factor, and results of strength tests*—Continued

1:2:4½ MIX GRADING NO. 2

Aggregate No.	$\frac{W}{C}$	Bags of cement per cubic yard	Modulus of rupture	Tensile strength	Compressive strength
			Lbs. per sq. in.	*Lbs. per sq. in*	*Lbs. per sq. in.*
40 (trap)	0.92	5.39	460	190	2,480
44 (siliceous gravel)	.90	4.87	450	165	2,440
46 (siliceous limestone)	.90	5.31	595	220	2,960
50 (siliceous gravel)	.91	4.98	490	190	2,600
60 (granite)	.93	5.14	480	200	2,600
61 (sandstone)	1.16	5.07	480	195	3,110
62 (cherty limestone)	.92	5.19	530	220	2,620
63 (argillaceous limestone)	1.09	5.31	465	220	2,870
64 (siliceous gravel)	.92	4.95	415	165	2,610
65 (siliceous gravel)	.90	4.93	470	165	2,540
66 (limestone gravel)	.92	4.97	525	205	2,650
67 (limestone gravel)	.96	4.94	500	230	2,960
68 (siliceous gravel)	.91	4.93	470	165	2,390
72 (shell limestone)	1.02	5.26	505	225	2,780

1:2:4½ MIX, GRADING NO. 3.

40 (trap)	0.96	5.31	465	195	2,440
44 (siliceous gravel)	.92	4.81	430	175	2,540
46 (siliceous limestone)	.94	5.26	540	215	2,710
50 (siliceous gravel)	.95	4.89	475	200	2,640
60 (granite)	.99	5.11	440	185	2,620
61 (sandstone)	1.23	4.95	480	180	2,880
62 (cherty limestone)	.99	5.17	500	195	2,490
63 (argillaceous limestone)	1.12	5.22	465	225	2,830
64 (siliceous gravel)	.94	4.95	430	170	2,750
65 (siliceous gravel)	.92	4.98	435	175	2,630
66 (limestone gravel)	.98	4.93	530	230	2,950
67 (limestone gravel)	1.00	4.95	515	215	2,800
68 (siliceous gravel)	.93	4.93	480	185	2,740
72 (shell limestone)	1.10	5.18	495	225	2,630

1:2:4½ MIX, GRADING NO. 4

40 (trap)	0.98	5.33	455	210	2,450
44 (siliceous gravel)	.95	4.84	420	160	2,250
46 (siliceous limestone)	1.00	5.18	570	220	2,470
50 (siliceous gravel)	.98	4.87	480	210	2,510
60 (granite)	1.03	5.06	465	205	2,500
61 (sandstone)	1.31	4.95	455	190	2,610
62 (cherty limestone)	1.01	5.18	525	200	2,430
63 (argillaceous limestone)	1.17	5.03	435	190	2,660
64 (siliceous gravel)	.93	4.85	405	165	2,430
65 (siliceous gravel)	.95	4.98	440	190	2,340
66 (limestone gravel)	.96	4.96	575	210	2,820
67 (limestone gravel)	1.03	4.94	515	235	2,820
68 (siliceous gravel)	.94	4.90	495	185	2,510
72 (shell limestone)	1.12	5.19	480	205	2,540

requirement due to gradation, within the limits used in this investigation is much less than the variation due to type of aggregate. It must be remembered in this connection that only reasonably uniform gradations were employed. For wide variations in grading the differences in the cement content would have been much greater.

In the construction of concrete pavements the cost of the materials is influenced to a large extent by the amount of cement required to produce a cubic yard of concrete. It has just been shown that the cement factor varied considerably with the different aggregates used in this investigation. If our only problem were to construct a slab containing concrete proportioned arbitrarily by volume, we would naturally select aggregates producing the highest yield. If, on the other hand, we had only to design a slab with a specified strength without considering economy, we might

select entirely different aggregates. The ideal aggregate is the one giving high strength and also high yield. By dividing the flexural strength of each aggregate by the corresponding cement factor, we obtain a series of values which may be used to compare these aggregates on a strength-yield basis. This has been done for the general average values and the results are shown in Figure 11. Examining the curve showing the relation between modulus of rupture and cement factor, we note that there are four aggregates which stand out above the others. They are Nos. 46, 62, 66, and 67 (two limestones and two limestone gravels), the same four that gave the highest flexural strength. There are four others, Nos. 50, 61, 68, and 72 which are grouped together while the remaining six, Nos. 40, 44, 60, 63, 64, and 65 show a rather low factor. With the exception of the trap and argillaceous limestone aggregates Nos. 40 and 63, the aggregates line up in somewhat the same order as they do in Figure 3.

These facts demonstrate that the increased strength developed by certain aggregates is not due entirely to increased cement content in terms of unit of volume of concrete. If the variations in strength were due to this cause alone, we should expect the strength-yield factors derived in the above manner to produce a horizontal line, instead of an ascending curve.

It is interesting to note that both the tension and compression graphs in Figure 11 present approximately the same order of ascending and descending values as in Figure 3. These values as well as the transverse test results discussed above indicate that the strength of the concretes must have been affected by factors inherent in the aggregates themselves as well as by the actual amount of cement present.

The ratios found between the strength in flexure, tension, and compression are given in Tables 9 and 10. It should be remembered that the compression specimens were broken four days after the flexure and tension specimens were broken which of course makes the ratio between tension and flexure the only true one. However, the other ratios are useful in making relative comparisons. Table 9 gives these ratios for each mix, while in Table 10 they are given for each grading. There is one point worthy of note in Table 9 and that is the ratios of tension to flexure for the different mixes. The 1:2:4½ mix showed about the same ratios as the 1:1.6:4 mix, both being low, while the 1:1.6:3 mix showed the highest values throughout. The tension-compression ratios are about the same for all four mixes, while the modulus-compression ratios are higher

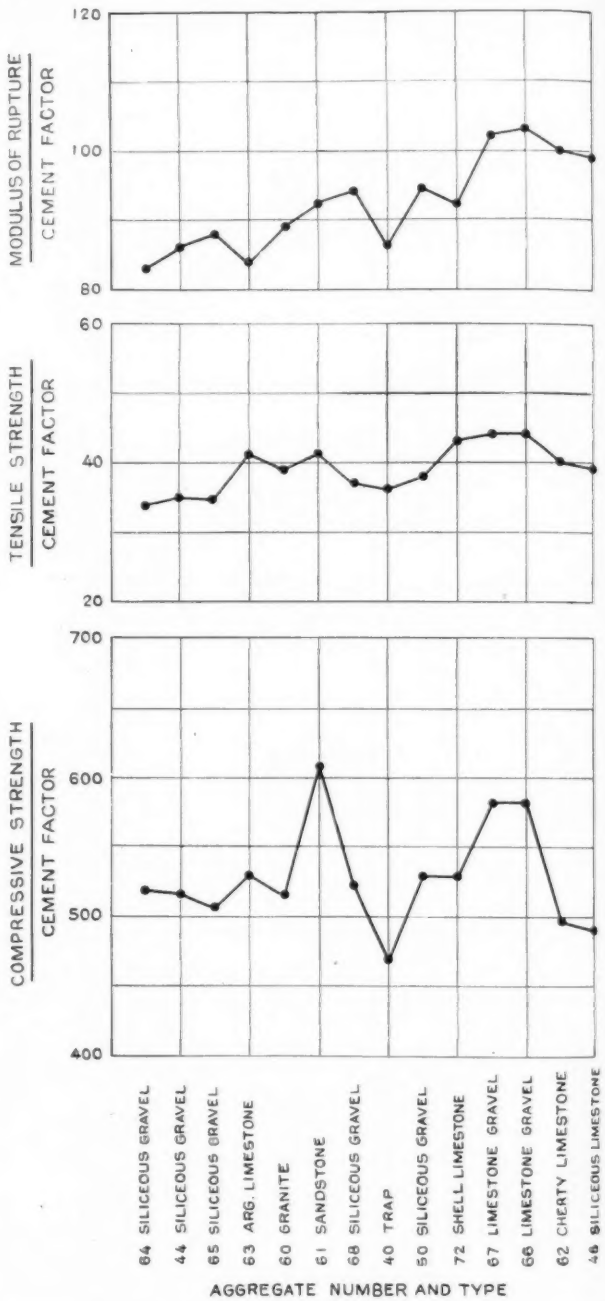

FIGURE 11.—RELATION BETWEEN CEMENT FACTOR AND FLEXURAL, TENSILE, AND COMPRESSIVE STRENGTHS, AVERAGE OF ALL TESTS

for the lean mixes. These tables, show in general, that the same ratios do not exist between the three types of tests for all aggregates.

TABLE 9.—*Ratios between strength in flexure, tension, and compression for each mix (average of four gradings)*[1]

Aggregate No.	1:1.6:3			1:1.6:4			1:2:4			1:2:4½		
	Ten./Mod.	Ten./Comp.	Mod./Comp.	Ten./Mod.	Ten./Comp.	Mod./Comp.	Ten./Mod.	Ten./Comp.	Mod./Comp.	Ten./Mod.	Ten./Comp.	Mod./Comp.
40	0.44	0.077	0.176	0.38	0.070	0.186	0.43	0.079	0.185	0.42	0.080	0.189
44	.44	.071	.160	.39	.064	.161	.43	.072	.167	.38	.068	.177
46	.42	.080	.188	.38	.077	.202	.41	.084	.206	.37	.077	.210
50	.44	.074	.166	.39	.067	.173	.44	.077	.187	.39	.074	.189
60	.47	.075	.162	.41	.073	.179	.43	.075	.175	.40	.073	.181
61	.50	.068	.135	.43	.065	.152	.43	.074	.166	.41	.067	.164
62	.44	.079	.181	.38	.078	.205	.40	.084	.212	.39	.081	.210
63	.50	.077	.152	.48	.077	.160	.48	.078	.163	.47	.075	.160
64	.42	.066	.156	.39	.061	.157	.44	.072	.164	.38	.062	.163
65	.43	.071	.166	.38	.065	.171	.40	.070	.173	.38	.069	.184
66	.45	.075	.169	.42	.074	.176	.43	.076	.177	.40	.076	.190
67	.48	.077	.162	.41	.073	.176	.39	.073	.186	.43	.079	.183
68	.44	.075	.169	.38	.068	.178	.39	.073	.187	.36	.068	.185
69	.53	.095	.179				.44	.089	.200			
70	.52	.087	.166				.48	.090	.188			
71	.50	.082	.165				.44	.085	.192			
72	.52	.083	.159	.44	.077	.175	.46	.082	.181	.43	.081	.190
Average	.47	.077	.165	.40	.071	.175	.43	.078	.183	.40	.074	.184

[1] Flexure and tension specimens broken at 29 days, compression specimens broken at 33 days.

TABLE 10.—*Ratios between strengths in flexure, tension, and compression for each grading (average of four mixes)*[1]

Aggregate No.	Grading No. 1			Grading No. 2			Grading No. 3			Grading No. 4		
	Ten./Mod.	Ten./Comp.	Mod./Comp.	Ten./Mod.	Ten./Comp.	Mod./Comp.	Ten./Mod.	Ten./Comp.	Mod./Comp.	Ten./Mod.	Ten./Comp.	Mod./Comp.
40	0.40	0.074	0.182	0.41	0.076	0.186	0.41	0.075	0.181	0.44	0.081	0.185
44	.38	.064	.169	.42	.068	.163	.43	.069	.162	.44	.075	.169
46	.35	.072	.205	.39	.076	.191	.42	.082	.196	.42	.088	.211
50	.36	.065	.181	.41	.071	.172	.43	.073	.172	.44	.082	.186
60	.39	.067	.170	.42	.074	.178	.44	.073	.165	.47	.085	.182
61	.45	.068	.152	.44	.065	.148	.43	.067	.156	.47	.072	.155
62	.39	.077	.198	.40	.078	.193	.41	.080	.195	.41	.088	.215
63	.46	.073	.159	.48	.075	.157	.50	.078	.156	.49	.081	.164
64	.38	.062	.163	.42	.066	.156	.39	.063	.159	.43	.069	.161
65	.36	.063	.177	.40	.070	.176	.40	.065	.164	.43	.076	.176
66	.41	.071	.175	.43	.076	.174	.44	.076	.171	.42	.080	.190
67	.38	.070	.182	.43	.073	.171	.45	.078	.173	.46	.082	.176
68	.36	.064	.181	.39	.070	.177	.41	.072	.178	.43	.077	.180
72	.42	.075	.177	.47	.079	.169	.47	.084	.178	.48	.085	.176
Average	.39	.069	.177	.42	.073	.172	.43	.074	.172	.45	.080	.180

[1] Flexure and tension specimens broken at 29 days, compression specimens broken at 33 days.

Data Indicate Desirability of Proportioning Concrete by Trial Method

The preceding discussion has demonstrated quite conclusively that the water-cement ratio alone does not control the strength of the concrete. It has been shown that the various coarse aggregates which are in common use today in the construction of pavements may have certain qualities inherent in the aggregates themselves which may cause a wide variation in strength for a given water-cement ratio. Further analysis of the data, however, shows equally well that for any given aggregate, variations in the water-cement ratio will affect the strength substantially in accordance with the well established fundamental law. This fact is of considerable assistance in connection with the design of concrete paving mixtures to meet certain strength requirements, as will be discussed below.

In Figure 12 there has been plotted for each aggregate the relation between the water-cement ratio and the strengths in flexure, tension, and compression. Before plotting these curves an attempt was made to correct the apparent water-cement ratios, as shown in the tables, for absorption of coarse aggregate. It was found, however, that certain of the aggregates were so nonhomogeneous that it was impossible to obtain reasonable concordance on repeated tests for absorption. These discrepancies were so great in a number of cases as to lead to the conclusion that the present standard method of making absorption tests on small 1,000-gram samples is practically worthless for nonhomogeneous aggregates. Attempts to make mathematical corrections were therefore abandoned and values corresponding to the average water-cement ratios for aggregates having little or no absorption

were adopted for each of the four mixes. It was felt that under the circumstances this was the most logical method of showing this relationship because it assumes that, if it had been possible to make an accurate correction for absorption, the net water-cement ratios for all the aggregate for a given mix would have been approximately the same. The only other variable which might affect this assumption is the shape of the aggregate fragments. It seems reasonable to suppose that, other things being equal, an aggregate having rounded surfaces would require less water than one having angular surfaces. However, inspection of Table 6 fails to reveal any significant differences which may be attributed to this factor. It is felt, therefore, that the water-cement ratios assumed for use in the charts are reasonably close to the true values, with the possible exception of aggregates Nos. 61 and 63, both of which were very highly absorptive.

Referring now to Figure 12, it will be observed that for all three types of test the strength decreases proportionately with increases in the water-cement ratio, resulting in a series of substantially parallel curves each of which represents the strength-water ratio relation for a given aggregate. For purposes of studying the effect of mineral composition the aggregates have been grouped into four divisions, the six calcareous materials being indicated by crosses, the single sandstone by an ×, the trap by an open circle, and the various materials which are essentially siliceous, such as the quartz gravels and the granite, by solid circles. The grouping of materials by types as previously discussed is at once apparent. Of interest, also, is the fact that, in so far as tensile strength is concerned, the curves are practically horizontal for water-cement ratios between 0.8 and 0.94. Aside from this the relation between strength and water-cement ratio follows the well known law fairly closely for each type of test.

The fact that these water-cement ratio-strength curves are practically parallel gives us a method of designing concrete paving mixtures by trial as described in the paper, The Design of Concrete Paving Mixtures by the Water-Cement Ratio Method, which appeared in the August, 1928, issue of PUBLIC ROADS. This method consists essentially in determining for any given water-cement ratio, say 0.8, and for each combination of aggregates under consideration, the transverse strengths at 28 days under standard laboratory conditions. The resulting values are then plotted and curves drawn through each parallel to the basic water-cement ratio-strength curve.

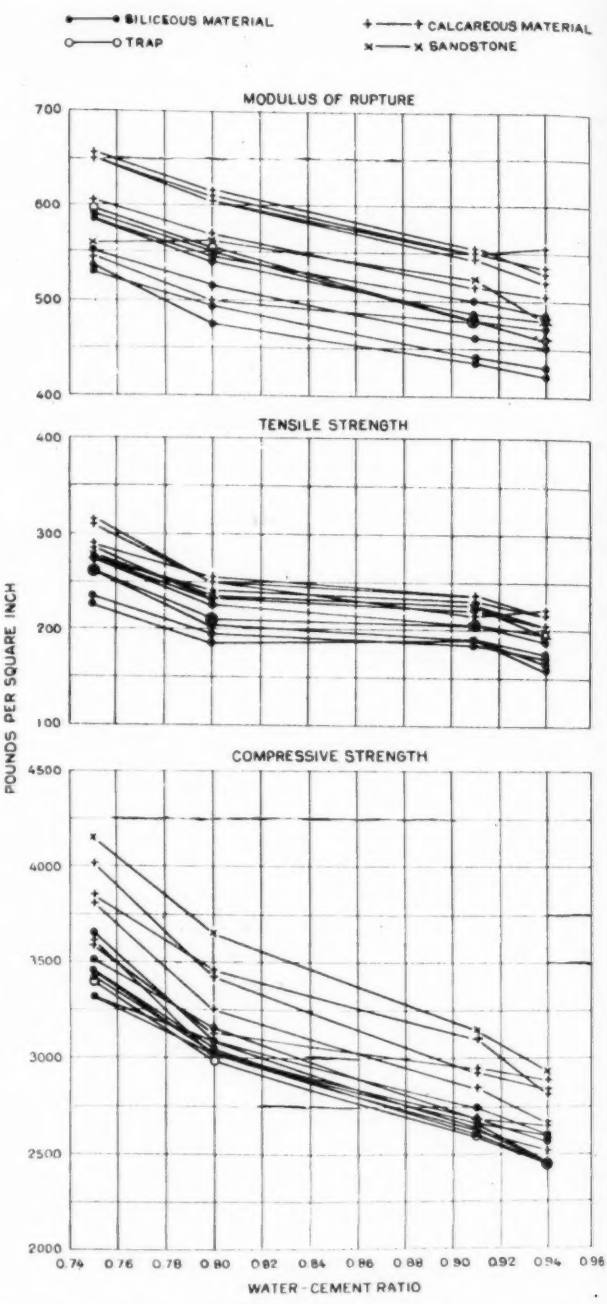

FIGURE 12.—RELATION BETWEEN WATER CEMENT RATIO AND FLEXURAL, TENSILE, AND COMPRESSIVE STRENGTH

By noting the water-cement ratio at which each of these curves cuts the design strength line, the proportions which must be used in the case of each aggregate to secure the design strength with the desired work-

ability may be determined by trial, from which in turn may be determined the quantities of materials in each case for a unit volume of concrete. A study of the relative costs of materials will then fix, in general, the most economical combination to use.

Conclusions

Based on the variables included in this investigation and the resulting test data, the following conclusions are drawn:

1. That the tensile, flexural and compressive strength of concrete are affected appreciably by the character of the coarse aggregate used.

2. That the tensile and flexural strength are affected to a greater extent than the compressive strength.

3. That for a given aggregate there is a fairly well defined relation between the strength of the concrete and the water-cement ratio.

4. That variations in the character of the coarse aggregates, other things being equal, may result in a difference in flexural strength equal to that produced by an appreciable change in the water-cement ratio with any given aggregate. (In this study, for instance, aggregate No. 46, with a water-cement ratio of 0.94, produced concrete of somewhat higher flexural strength than aggregate No. 44, with a water-cement ratio of 0.74—a difference of 0.2).

5. That there is a fairly definite relation between certain mineralogical characteristics of the coarse aggregate and the strength of concrete, calcareous aggregates in general giving consistently higher flexural and tensile strength than siliceous aggregates.

6. That, in general, aggregates having rounded fragments produced concrete of lower flexural and tensile strength than aggregates which are composed wholly or in part of cushed fragments.

7. That, within the limits of this study, variations in grading of coarse aggregates have no consistent effect upon the strength of concrete. (It is not to be inferred from this statement, however, that control of grading is not important. Variations in grading occurring during construction not only affect yield when measurements are made by volume but also affect the workability and therefore the uniformity of the concrete).

8. That, within the range in quality covered by this study, there is no relation between the quality of the coarse aggregate, as measured by the abrasion test, and the strength of the concrete.

Committee Appointments for 1929 Announced

Appointments to the standing committees of the Association for 1929 have recently been completed by President Wise and are given below for the information of the membership. Suggestions and information relative to the work of any of these committees will be more than welcomed by the respective chairmen.

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The Crushed Stone Journal

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NATIONAL CRUSHED STONE ASSOCIATION
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WASHINGTON, D. C.

J. R. BOYD, Editor

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Conference Held with American Railway Association on Cleaning and Repairing Cars

IT will be remembered that during last year a questionnaire was sent out from Association headquarters to all producers of crushed stone designed to obtain data relative to the expense to the industry of cleaning and repairing railroad cars placed at producers' plants for loading. Simultaneous with the efforts of the National Crushed Stone Association, the National Sand and Gravel Association and the National Slag Association also obtained similar information from their respective industries with the thought in mind that a joint presentation of the data pertinent to this subject would be more effective, when placed before the American Railway Association, than if each industry acted singly.

The answers to the questionnaires sent out by all three industries have now been compiled and analyzed and in accordance with the original intention an informal conference was recently held in Washington with officials of the American Railway Association. The National Crushed Stone Association was represented by F. T. Gucker, President of the John T. Dyer Quarry Co., Norristown, Pennsylvania, who is Chairman of the Association's Car Servicing Committee.

From the very beginning it was conceded that the mineral aggregates industries were bearing a severe burden in being forced to expend annually approximately one million dollars to clean and repair railroad cars placed at their plants for loading in order that they might be put in safe condition for the transporting of their materials. It is true that the law requires that a shipper be provided with a car which will safely transport its cargo to destination but it more frequently happens than otherwise that the shipper in order to insure prompt and efficient service is placed under the necessity of cleaning and repairing unsuitable cars at his own personal expense, rather than take advantage of the alternative of rejecting the cars. Considered from the viewpoint of the railroads it was pointed out that many practical difficulties are encountered in attempting to police the cleaning and repairing of cars by consignees and further that a necessarily heavy expense is involved in removing a few bad cars from a string of empties ready for switching to a producer's plant for loading.

The American Railway Association gave every indication of sympathetically understanding the viewpoint of aggregates shippers, recognizing that the problem was one of mutual interest and pledged its full cooperation in an effort to work out a solution which would materially lessen the burden of expense now unjustly falling upon the shippers. Such a solution can only be effected through the cooperation of the railroads, shippers and consignees. Full details relative to the program which is ultimately decided upon will be published at a later date.

Pending the formulation of a definite program, it would be helpful if instances in which cars are in unusually bad condition were promptly called to our attention in order that steps may be taken with the proper authorities to afford immediate relief.

Committee Appointments for 1929 Announced

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(*Continued from page* 25)

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UMI

Further Tests on Crushed Stone and Gravel Concrete

(*Continued from page* 9)

loads. Consequently, if the modulus of rupture is low, the strength of the slab may be exceeded frequently, whereas, if the modulus of rupture is high, the safe working stress will likewise be high and may not be exceeded by the tensile stress produced by traffic. Therefore, concrete having low resistance to bending cracks frequently under the action of traffic and that having high resistance cracks infrequently because it is not over-stressed.

The important influence of aggregates on the modulus of rupture of road concrete thus becomes apparent. High-grade aggregates giving high modulus of rupture are much to be preferred for they provide a considerable safeguard against excessive cracking and early deterioration of concrete road slabs. Concrete for road slabs should be designed, not to have a given compressive strength, but to have a given modulus of rupture.

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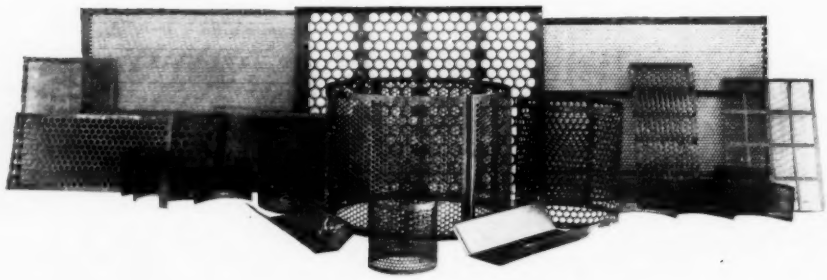

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